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STATUS OF DRY SO_2 CONTROL SYSTEMS:

FALL 1983

by

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16. ABSTRACT The report, on the status of dry SO2 control for utility and industrial boilers in the U.S., reviews current and recently completed research, development, and commercial activities. Dry SO2 control systems covered include: (1) spray dryers with a fabric filter or an electrostatic precipitator (ESP), (2) dry injection of alkaline material into flue gas accompanied by collection of product solids and fly ash in a fabric filter or an ESP, and (3) electron-beam (E-beam) irradiation. Spray drying and dry injection systems generally include a fabric filter or an ESP and control SO2 and particulate matter simultaneously; E-beam technology is designed to also control NOx. Spray drying continues to be the only technology commercially applied to utility and industrial boilers. The two new utility systems sold since the last status report (Fall 1982) bring the total utility spray drying flue gas desulfurization (FGD) capacity to about 7200 MWe. Also, 10 recently sold new industrial units bring the total of commercial industrial boiler unit sales to 21. Performance data for five utility systems and three industrial systems were recently published. Some full-scale systems that have come on-line since the last survey have experienced atomization problems and solids buildup on the dryer walls during initial operation. The first trona dry injection application has been announced for a 500 MWe unit.

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Coal		Dry SO2 Control	21D	13I
Combustion	Nitrogen Oxides	Fabric Filters	21B	
Boilers	Dust	Particulate	21A	11G
Utilities	Electron Beams	Electron-Beam Irradiation		20H
Spray Drying	Irradiation		13H	18H

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ABSTRACT

This report is the fifth on the status of dry SO_2 control for utility and industrial boilers in the United States.* The information presented is based on a review of current and recently completed research, development, and commercial activities. Dry SO_2 control systems covered include: (1) spray dryers with a fabric filter or an electrostatic precipitator (ESP), (2) dry injection of alkaline material into flue gas accompanied by collection of product solids and fly ash in a fabric filter or an ESP, and (3) electron-beam (E-beam) irradiation. Spray drying and dry injection systems generally include a fabric filter or an electrostatic precipatator and provide simultaneous SO_2 and particulate matter control while the E-beam technology is designed to provide simultaneous SO_2 and NO_x control.

Spray drying continues to be the only one of the technologies commercially applied to utility and industrial boilers. Two new utility systems have been sold since the last status report, bringing the total utility spray drying flue gas desulfurization (FGD) capacity to about 7,150 MWe. Also, 10 new industrial units have recently been sold, making a total of 21 commercial industrial boiler units. Performance data have recently been published for several commercial spray drying systems, including five utility systems, and three industrial systems. The full-scale systems that have come on-line since the last survey have generally met or exceeded SO_2 removal guarantees. Some of the systems, however, experienced atomization problems and solids build-up on the dryer walls during initial operation.

The first planned commercial application of trona dry injection technology has been announced for a 500 MWe unit.

Various research and development activities in the spray drying and E-beam areas are being funded by EPA, the Department of Energy (DOE), the Electric Power Research Institute (EPRI), and several process vendors.

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*Previous reports are available from the National Technical Information Service (First Survey: EPA-600/7-80-030; Second Survey: EPA-600/7-81-018; Third Survey: EPA-600/7-81-097; and Status Report - Fall 1982: EPA-600/7-83-041.)

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SECTION 1

INTRODUCTION

This report is the fifth on the status of dry flue gas desulfurization (FGD) processes in the United States for both utility and industrial applications.* Throughout this report, dry FGD will be defined as any process which involves contacting a sulfur-containing flue gas with an alkaline reagent and which results in a dry waste product for disposal. This includes (1) systems which use spray dryers for a contactor with subsequent baghouse or electrostatic precipitator (ESP) collection of waste products; (2) systems which involve dry injection of alkaline reagent into the flue gas with subsequent baghouse or ESP collection; and (3) systems which supply reagent to the flue gas followed by electron-beam irradiation. This definition of dry systems excludes several dry adsorption or "acceptance" processes, such as the Shell/UOP copper oxide process and the Bergbau-Forschung adsorptive char process since the status of these processes has been documented in previous EPA reports. Fluidized bed combustion and limestone injection into multistage burners (LIMB) have also been excluded because the status of these processes is being documented by EPA elsewhere.

Also excluded was the regenerable Rockwell Aqueous Carbonate Process (ACP) which, although based on SO_2 removal with a spray dryer, does not fit the limitation of this study as being a "throwaway" system. However, the open loop, spray dryer contactor portion of the Rockwell process has been adapted for a "throwaway" system and, as such, has been included here.

1.1 REPORT ORGANIZATION

Section 2 presents an overview of the major types of dry FGD processes considered in this report and includes:

- A summary of new developments in the dry FGD area.
- A discussion of the recent commercial and developmental activities for each type of process (spray drying, dry injection, and electron-beam irradiation).

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*Previous report numbers EPA-600/7-80-030, EPA-600/7-81-018, EPA-600/7-81-097, and EPA-600/7-83-041. (Available through National Technical Information Service.)

Section 3 presents descriptions of current and recently completed dry FGD research and development programs and commercial sales summaries. Section 4 provides a discussion of the results of recent cost studies on dry FGD systems. Finally, Section 5 provides information on the physical and chemical characteristics of dry FGD wastes.

1.2 TYPES OF DRY FGD SYSTEMS

This section provides a general process description for each of the three technologies being considered (i.e., spray drying, dry injection, and electron-beam irradiation). This background information is provided for the reader who may be unfamiliar with the technologies and is only intended to be a generalized description of the system.

Reagent ratio or sorbent stoichiometry for dry FGD systems, as used throughout this report, is defined as the moles of fresh reagent introduced to the system divided by the moles theoretically required for complete reaction with all the SO_2 entering the system. This definition results in a lower figure for the reagent ratio as compared to the conventional wet scrubbing definition, which is based on the moles of SO_2 removed by the system.

1.2.1 Spray Drying

Figure 1-1 is a schematic diagram of the spray drying FGD process. The gas containing fly ash and SO_2 enters the spray dryer and is contacted with a finely atomized alkaline slurry or solution. During the approximately 10-second residence time in the dryer, the flue gas is adiabatically humidified as the water in the slurry or solution is evaporated. Simultaneously, flue gas SO_2 reacts with the alkaline species to form solid sulfite and sulfate salts. The solids formed are dried to generally less than 1 percent free moisture. The flue gas, which has usually been humidified to within 11 to 28°C (20 to 50°F) of its adiabatic saturation temperature, passes through the dryer and into a downstream high efficiency particulate matter control device. In some designs a portion of the solids drop out of the dryer, but the bulk of the desulfurization products are collected with fly ash in a fabric filter or an ESP. The reaction between the alkaline material and flue gas SO_2 continues as the gas passes through the ductwork and the fabric filter or ESP.

Table 1-1 lists the major design and operating factors for spray drying FGD. These considerations are discussed in more detail below.

Using a spray dryer as a flue gas contactor involves adiabatically humidifying the flue gas to within a specified number of degrees above saturation. With set conditions for inlet flue gas temperature and humidity and for a specified approach to saturation temperature, the amount of water which can be evaporated into the flue gas is set by energy balance considerations. Liquid-to-gas ratios are generally in the range of 0.2 to

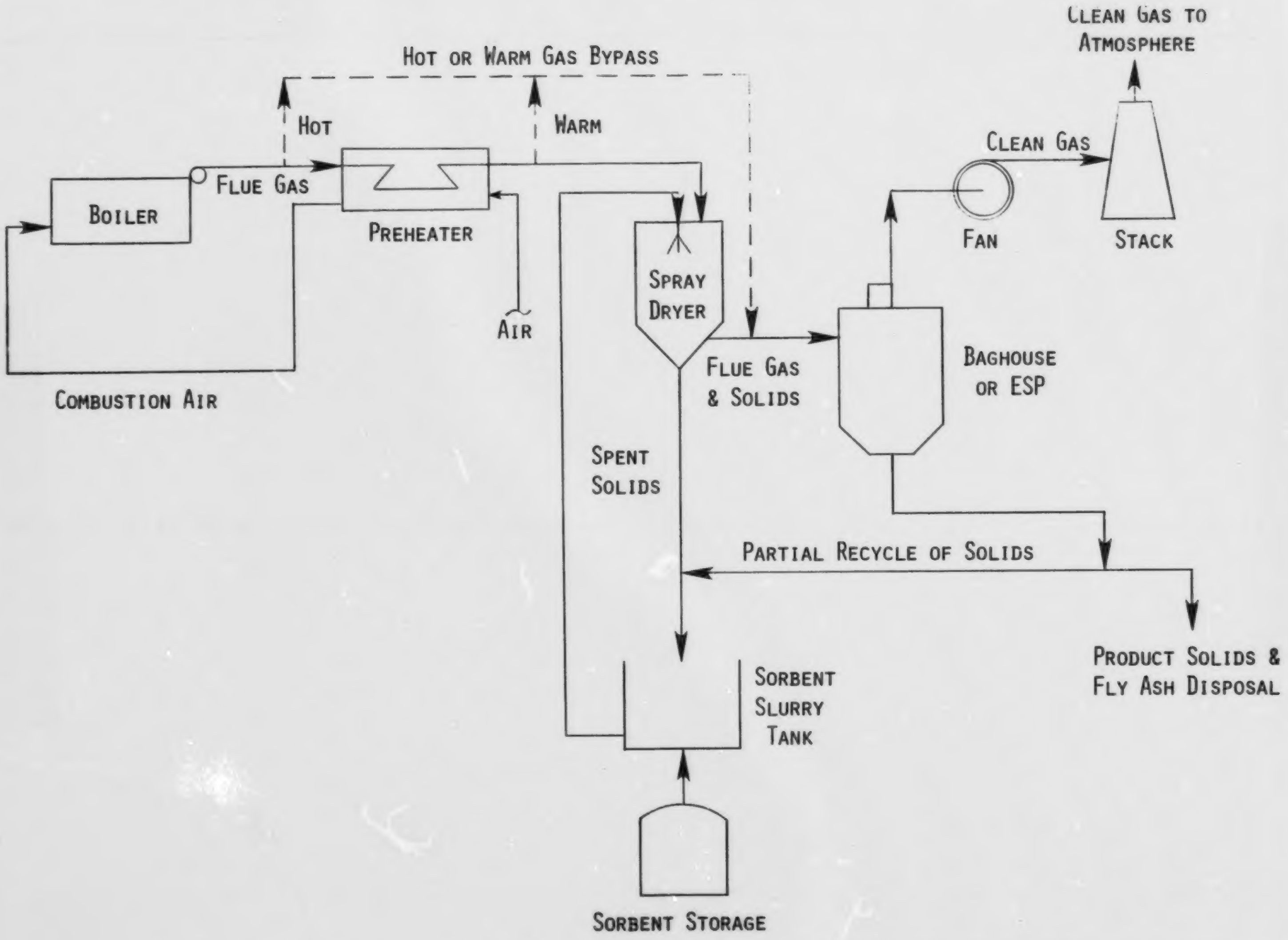
TABLE 1-1. IMPORTANT OPERATIONAL AND DESIGN FACTORS FOR SPRAY DRYING FGD SYSTEMS

Operational Factors

- Approach to saturation at dryer outlet
- Sorbent stoichiometry
- Inlet SO_2 concentration
- Temperature drop over the spray dryer
- Fly ash alkalinity
- Gas residence time

Design Factors

- Spray dryer design (gas distribution, gas exit configuration)
- Atomizer type
- Slaker type
- Use of solids recycle
- Use of flue gas bypass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Hot or Warm Gas Bypass
Hot
Warm
Clean Gas
Boiler
Flue Gas
Preheater
Fan
Stack
Spray Dryer
Air
Combustion Air
Flue Gas & Solids
Baghouse or ESP
Spent Solids
Partial Recycle of Solids
Product Solids & Fly Ash Disposal
Sorbent Slurry Tank
Sorbent Storage

Figure 1-1. Typical spray dryer/particulate collection flow diagram.

0.3 gal/ft^3).* The sorbent stoichiometry is varied by raising or lowering the concentration of a solution or weight percent solids of a slurry containing this set amount of water. While holding other parameters such as temperature constant, the obvious way to increase SO_2 removal is to increase sorbent stoichiometry. However, as sorbent stoichiometry is increased to raise the level of SO_2 removal, two limiting factors are approached:

- Sorbent utilization decreases, raising sorbent and disposal costs.

- An upper limit is reached for the solubility of the sorbent in the solution, or for the weight percent of sorbent solids in a slurry.

There are at least two methods of circumventing these limitations. One method is sorbent recycle, using the solids that have either dropped out in the spray dryer or collected in the particulate emission control device. Recycle increases sorbent utilization and can also increase utilization of any alkalinity in the fly ash.

The second method of avoiding the above limitations on SO_2 removal is to operate the spray dryer at a lower outlet temperature; that is, a closer approach to saturation. Operating the spray dryer at a closer approach to saturation has the effect of increasing both the residence time of the liquid droplets and the residual moisture level in the dried solids. As the approach to saturation decreases, SO_2 removal rates and sorbent utilization generally increase dramatically.

The approach to saturation at the spray dryer outlet is set by either the requirement for a margin of safety to avoid condensation in downstream equipment or restrictions on stack temperature. The spray dryer outlet can be operated at temperatures lower than these restrictions would otherwise allow if some warm or hot gas is bypassed around the spray dryer to reheat the dryer outlet gas. Warm gas (from downstream of the boiler air heater) entails no energy penalty, but bypassing untreated gas for reheating can limit overall SO_2 removal efficiencies. Significantly less hot gas (upstream of the air heater) is required for heating, but using hot gas decreases the energy available for air preheating. Figure 1-1 illustrates these two reheat options.

Several similarities exist between the designs of the commercial spray drying FGD systems sold to date. All of the systems except one use lime as the sorbent; the exception uses commercial soda ash. In addition, all but three of the purchased systems include a fabric filter for collection of fly ash and waste products. Three utility systems will have an ESP instead of a fabric filter. Reverse-air fabric filters have been selected for utility systems, while pulse-jet units have been the choice for most industrial systems.

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*To conform with general engineering practice, English Engineering units rather than metric units are normally used in this report. Appendix A provides conversion factors from English Engineering to International System (SI) units.

Most commercial system designs use rotary atomizers, although nozzle atomizers are used in some designs. Solids recycle and flue gas bypass for limited reheat are site-specific design options. Recycle, however, is being included more often than not, primarily because it improves sorbent utilization and lowers reagent costs. The use of recycle and flue gas bypass depends primarily on the SO_2 removal requirements.

Several differences between the commercialized designs of spray dryer FGD systems are evident. The differences can be categorized into four major areas:

- Spray dryer design and operation.
- Atomization.
- Sorbent preparation (lime slaking).
- Fabric filter design and operation.

Variations in spray dryer design include the shape of the dryer, gas disperser configurations, multiple or single rotary (or nozzle) atomizers per dryer, one- versus two-point flue gas admission to the spray dryer, and solids collection from the spray dryer. Each vendor claims his design to be suitable for FGD and to have certain advantages. Some important considerations in evaluating the various designs include:

- Liquid/gas contact.
- Turndown capability.
- Potential for plugging or carryover of wet solids to baghouse during upset conditions.

Differences in spray dryer operation include gas residence time and the approach to saturation at the dryer outlet. Gas residence times range from 7 to 12 seconds in most commercial designs; most operate in the 10- to 12-second range. Many commercial system designs call for a relatively close approach to saturation at the dryer outlet. These close approaches are common where SO_2 removal efficiency requirements approach 85 to 90 percent, but they may also be used to decrease reagent use in lower removal efficiency applications. Some designs, however, are based on a wider approach to saturation.

Atomization techniques vary with regard to the use of rotary or nozzle atomizers, atomizer wheel speed in rotary atomizers, atomizing fluid (air or steam) for nozzles, internal or external mixing of fluids in nozzles, and the number of atomizers. Rotary atomizers may be used on a single or multiple atomizer per dryer basis. Several commercial utility systems use three atomizers per dryer, but most sold to date have a single atomizer per dryer. Rotary atomizers are generally thought to have certain advantages over nozzle atomizers. Specifically, unlike nozzle atomization, the size of the droplets produced by rotary atomizers is independent of slurry flow rate, providing for good turndown capability. Some plugging problems have occurred in nozzles using steam for atomization. One potential advantage of nozzle atomizers lies in the fact that they are mechanically simpler than rotary atomizers.

The method used to slake the lime also varies for commercial system designs. Ball mill, paste, and detention slakers are all used, but ball mill and paste slakers are more common. Each method is perceived to have certain advantages. Ball mill slakers generally produce a more finely ground and possibly more reactive slurry and, unlike paste slakers, no grit removal and disposal are required. Paste slakers, on the other hand, have lower capital costs, lower noise levels, and lower power requirements. Also, they generally produce a less abrasive slurry than do ball mills, which could reduce the potential for wear and maintenance of system pumps and piping.

As stated above, fabric filters have been chosen over ESPs in most of the commercial spray drying applications to date. Fabric filters may have an advantage over ESPs in that unreacted alkalinity in the solids and fly ash collected on the fabric surface can react with remaining SO_2 in the flue gas as the gas passes through the fabric filter. Some process developers have reported that SO_2 removal across the fabric filter can account for at least 10 percent of the total system SO_2 removal. In some applications, however, an ESP might be more desirable than a fabric filter. The factors that are important in making the choice between ESPs and fabric filters include:

- Use of recycle (increases dust loading to ESP, thus increasing ESP size and cost).
- Fly ash resistivity (high ash resistivity often requires larger, more expensive ESPs).
- Pressure drop (an ESP has a lower pressure drop and related costs than a fabric filter).

Fabric filter designs for spray dryer FGD systems vary primarily with regard to bag fabric, cleaning frequency, and cleaning mode. Other more subtle variations, too numerous to mention, between the well-established fabric filter design practices of the different vendors also exist. Teflon-coated fiberglass bags have been selected for many systems, although acrylic bags may be a lower cost alternative for low gas temperatures.

1.2.2 Dry Injection

A generalized flow diagram of the dry injection process is shown in Figure 1-2. The process involves pneumatic injection of a dry, powdery sodium compound into the flue gas with subsequent particulate collection in a fabric filter. The point of alkali injection may vary from upstream of the air preheater to the inlet of the fabric filter. Reaction between the reagent and SO_2 occurs both in the duct and on the filter bag surface.

Although other alkaline reagents (e.g., lime and limestone) have been tested, only certain sodium compounds have shown the capability for high SO_2 removal from the flue gas. Nahcolite and trona ores, which contain naturally occurring sodium compounds, appear to be the most promising reagents for dry injection in terms of reactivity and cost. Nahcolite, which is usually associated with western oil shale reserves, contains about 80 percent sodium bicarbonate ($NaHCO_3$). Trona ore, which is found in large deposits in Wyoming and California, contains sodium carbonate (Na_2CO_3) and sodium sesquicarbonate ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$). Nahcolite has been shown to be somewhat more reactive with SO_2 in the flue gas than trona.

The principal reaction product from nahcolite and trona injection is sodium sulfate (Na_2SO_4), according to the following overall reactions (1):

$$2NaHCO_3 + SO_2 + \tfrac{1}{2}O_2 \rightarrow Na_2SO_4 + 2CO_2 + H_2O$$

$$2(Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O) + 3SO_2 + 3/2\ O_2 \rightarrow 3Na_2SO_4 + 4CO_2 + 5H_2O$$

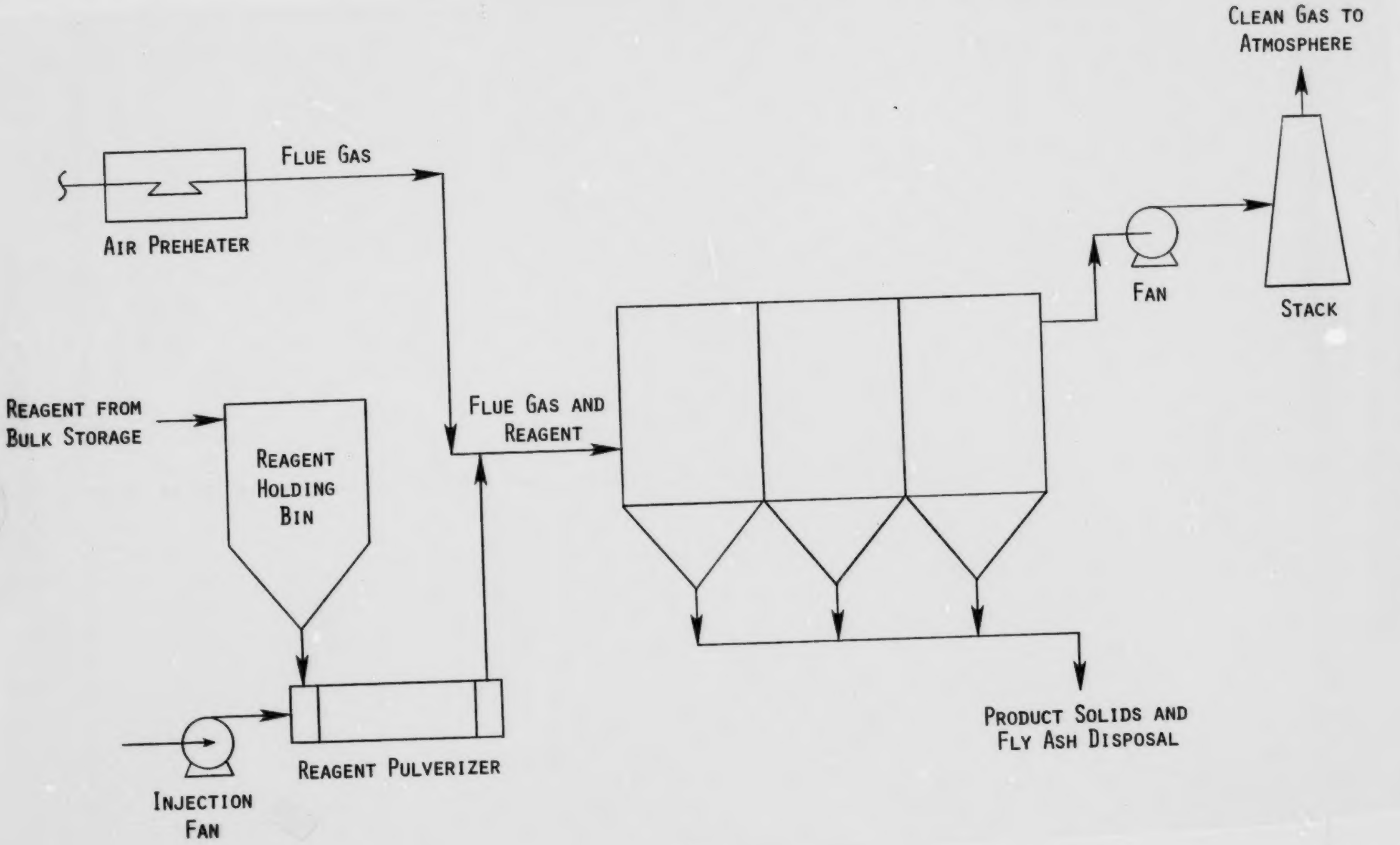
Major factors that affect SO_2 removal by nahcolite and trona injection include stoichiometric ratio and the flue gas temperature at the point of injection. Higher SO_2 removals are obtained at higher normalized stoichiometric ratios (equivalent moles Na_2O per mole of inlet SO_2). However, higher stoichiometric ratios also result in lower reagent utilization. Injection of the reagent at too low a temperature will reduce the initial SO_2 reaction rate and may limit overall SO_2 removal. For nahcolite it appears that SO_2 removal drops off dramatically at injection temperatures below 135°C (275°F) (2).

Other parameters that are important in the dry injection process include reagent particle size, mode of injection (batch, semi-batch, or continuous), baghouse air-to-cloth ratio, and bag cleaning frequency.

1.2.3 Electron-Beam Process

The electron-beam (E-beam) process involves the irradiation of flue gas containing a reactant, such as ammonia or lime. The process removes both SO_2 and NO_x from the flue gas and results in a dry waste product.

A schematic diagram of the E-beam/ammonia process is shown in Figure 1-3. In this process, flue gas from a fly ash collection device is cooled and humidified in a quench tower. The resulting gas moisture content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Air Preheater
Fan
Stack
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Bulk Storage
Reagent
Holding
Bin
Flue Gas and
Reagent
Injection
Fan
Reagent Pulverizer
Product Solids and
Fly Ash Disposal

Figure 1-2. Dry alkali injection flow diagram.

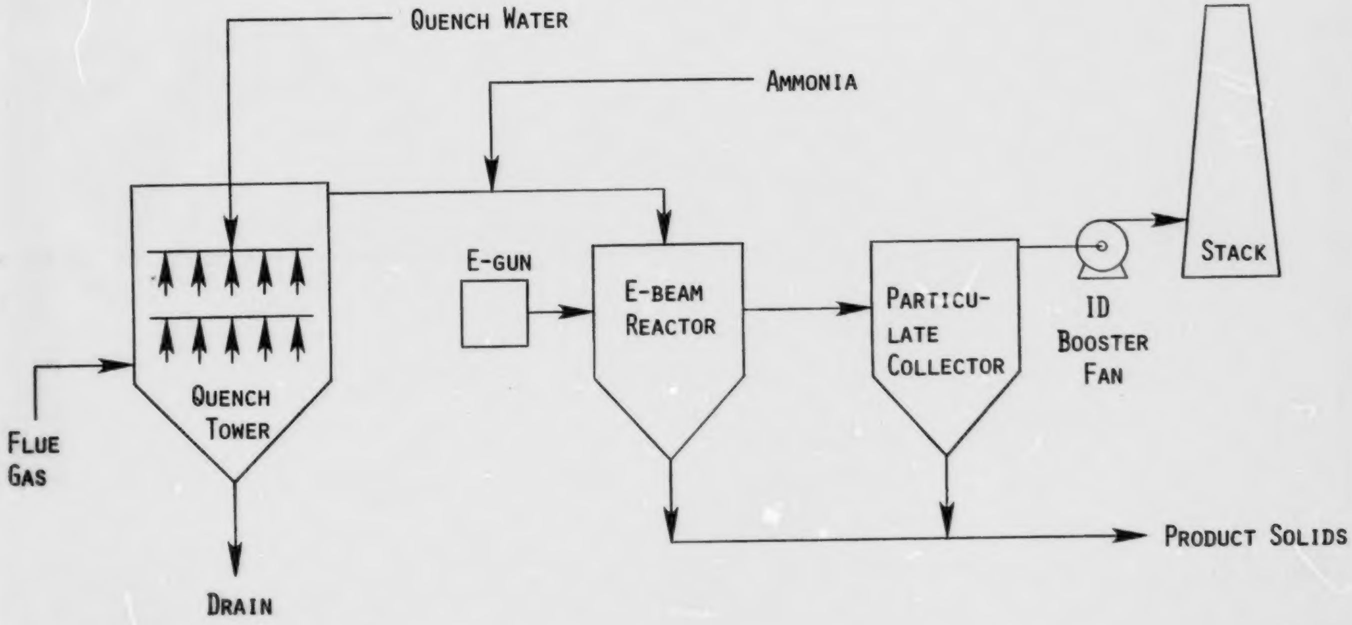
QUENCH WATER
AMMONIA
STACK
E-GUN
E-BEAM REACTOR
PARTICU- LATE COLLECTOR
ID BOOSTER FAN
FLUE GAS
QUENCH TOWER
DRAIN
PRODUCT SOLIDS

Figure 1-3. E-beam/ammonia process flow diagram.

is about 10 percent. Ammonia is injected into the cooled gas and the gas is passed through an E-beam reactor. In the reactor, oxygen and water are excited and ionized to form the radicals [OH], [O], and [HO_2] by the application of electrons at a dose of 1 to 3 Mrads (1 Mrad is equivalent to 10 joules/g of flue gas). These radicals react with SO_2 and NO_x to form sulfuric acid (H_2SO_4) and nitric acid (HNO_3). The acids are neutralized by ammonia and water in the flue gas to form solid ammonium sulfate (NH_4SO_4) and ammonium sulfate nitrate [$(NH_4)_2SO_4 \bullet NH_4NO_3$]. The reaction time for formation of the sulfate and nitrate salts is less than 1 second. Product solids are collected in a hopper below the E-beam reactor or in a downstream particulate collector.

In another version of the E-beam process, shown in Figure 1-4, the water quench tower is replaced with a lime-based spray dryer. SO_2 is removed from the flue gas in the spray dryer, and NO_x and additional SO_2 are removed in the E-beam reactor. Reactions in the E-beam reactor to form sulfuric and nitric acids occur in the same manner as in the ammonia process. The acids are neutralized by $Ca(OH)_2$ to form calcium salts [$CaSO_4$, $Ca(NO_3)_2$, and $CaSO_3$].

Bench- and pilot-scale studies of E-beam processes have shown that variables important to performance include gas moisture content, gas temperature, oxygen content, reagent ratio, and electron dosage.

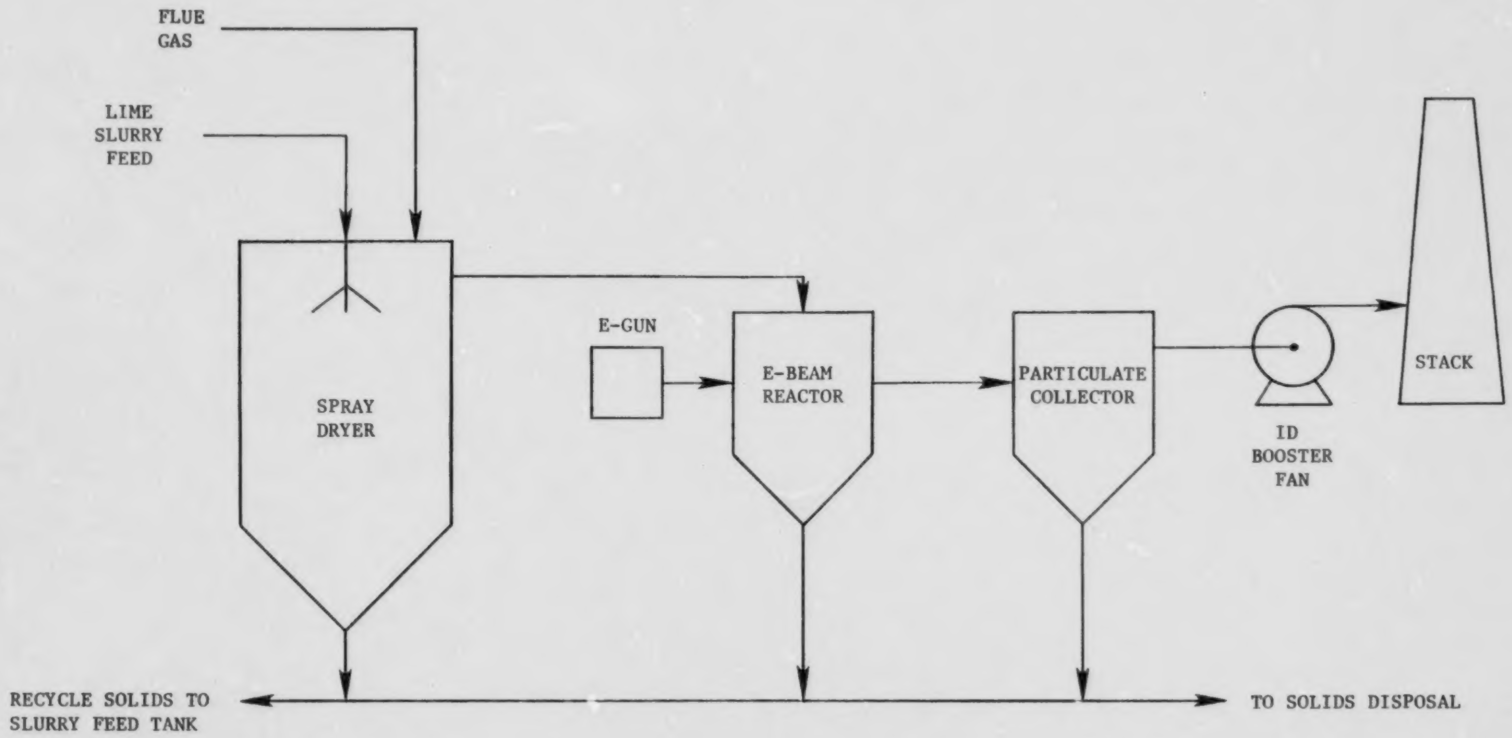
FLUE
GAS
LIME
SLURRY
FEED
SPRAY
DRYER
E-GUN
E-BEAM
REACTOR
PARTICULATE
COLLECTOR
ID
BOOSTER
FAN
STACK
RECYCLE SOLIDS TO
SLURRY FEED TANK
TO SOLIDS DISPOSAL

Figure 1-4. The E-beam/spray dryer process flow diagram.

1.3 REFERENCES

1. Davis, W. T. and T. C. Keener. Chemical Kinetics Studies on Dry Sorbents - Literature Review. (Prepared for U. S. Department of Energy, Grand Forks, North Dakota.) Publication No. DOE/FC/10184-2, August 10, 1980. pp. 42-56.

2. Muzio, L. J., et al. (KVB, Inc. and Electric Power Research Institute). 22-MW Demonstration of Dry SO_2 Scrubbing with Sodium Sorbent Compounds. Paper # 83-38.5, presented at the 76th Annual Meeting of the Air Pollution Control Association, Atlanta, Georgia, June 1983.

SECTION 2

OVERVIEW

Interest in dry SO_2 control has remained strong since the last status report was prepared in Fall 1982. Two new utility systems and 10 new industrial spray drying units have been sold. Seven utility systems and 10 industrial units are now operational, and operating experience with several of these systems has been reported. New information has been published on the use of spray drying for high sulfur coal applications, an area that is the focus of several of the current or recently completed pilot- and demonstration-scale test programs. Also, the first planned commercial application of dry injection technology has been announced, following the completion of a demonstration-scale test program. Plans for the construction and testing of electron-beam (E-beam) irradiation pilot plants have been finalized, and testing of the E-beam/lime spray drying version of the process is now underway.

Section 2.1 provides a summary of new developments in dry SO_2 control for utility and industrial boilers. Sections 2.2 through 2.4 provide more detail on the recent activities involving each of the technologies covered in this status report: spray drying, dry injection, and electron-beam irradiation.

Work is also continuing in the waste disposal area. Recent studies are focused on characterizing solid waste properties as a function of coal type and FGD process conditions. Waste disposal-related activities are discussed in Section 5 of this report.

2.1 SUMMARY OF NEW DEVELOPMENTS

Spray drying continued to be the only dry SO_2 control process commercially applied to utility or industrial boilers. Two new utility systems were awarded since the last status report, bringing the total utility spray drying FGD capacity to about 7,150 MWe. This total includes the 110 MWe demonstration system at the Northern States Power Company (NSP) Riverside Station, which is now being operated by the utility.

Ten new industrial units have been awarded since late 1982 for three Federal government installations (one Navy and two Air Force). The industrial systems now sold total 21 units.

Performance and compliance test results were recently reported for four utility systems, including Basin Electric's Antelope Valley (Unit No. 1) and Laramie River (Unit No. 3) Stations, United Power Association's Stanton Station and Marquette Board of Light and Power's Shiras Station. Test results were also reported for the industrial systems at Argonne National Laboratory, Austell Box Board Company and Container Corporation. Data from EPA/EPRI-funded testing at the NSP Riverside Station and the results from pilot-scale testing funded by EPRI, EPA, and DOE have also been published. In general, the performance test results have shown that the commercial systems have met or exceeded SO_2 and particulate matter removal guarantees, except for the Laramie River system which is still undergoing further process development and optimization. Recently published data have confirmed earlier indications that 90 percent or greater SO_2 removal is achievable for high sulfur coal applications (3 to 4 percent sulfur coal with a corresponding inlet SO_2 concentration of 2,000 to 2,500 ppmv). More detail on these performance and pilot tests is given in Section 2.2.

Several commercial spray drying systems have only recently become operational, and compliance and performance testing is planned for early 1984. At least one other system is in the initial startup stage and one additional system should be in start-up or performance test stages by the end of 1984.

Vendors report having several utility and industrial system bids under evaluation with at least two industrial system awards expected by mid-1984. The market outlook for utility systems, particularly for retrofits, is improving with the growing concern over acid deposition, and the market outlook for industrial systems has improved with the recent economic upturn.

A major development in spray drying during the past 2 years has been the successful application of the technology to higher sulfur coal-fired boilers. Data have recently been made available from the industrial system at Argonne National Lab, EPA/EPRI-funded Riverside process tests and DOE-funded tests at Babcock and Wilcox's Alliance Research Center. Most of these tests were conducted at flue gas inlet SO_2 concentrations of 1,900 ppmv or greater. The data confirm earlier high sulfur test results which showed that, at a relatively close approach to saturation of 18° to 20°F, reagent ratios of at least 1.3 are required to achieve 90 percent SO_2 removal.

A novel spray drying process for simultaneous SO_x/NO_x removal has been developed by Joy Industrial Equipment Company and Niro Atomizer, Inc. The process, which involves lime-based spray drying with NaOH addition, has been demonstrated on the pilot-, industrial-, and utility-scales. NO_x removals of 50 to 60 percent with concurrent SO_2 removals of 90 to 95 percent have been reported. Also, the capability of calcium chloride addition to reduce lime consumption in spray drying systems was demonstrated on a utility scale during the EPA/EPRI testing at the NSP Riverside Station.

Operating experience with full-scale commercial systems has been reported as relatively trouble-free. However, some systems experienced problems with atomizer pluggage, inadequate gas/liquid mixing, and build-up of wet solids on the dryer walls during initial operation. Major operating problems encountered with full-scale systems in the past year are discussed with the commercial activities of the respective system vendors in Section 3.

Spray drying demonstration- and pilot-scale testing and research continue to focus on refinement of spray dryer design and operation, comparison of rotary and nozzle atomizers, investigation of the benefits of solids recycle, and characterization of ESP's downstream of the spray dryer. Other areas of spray dryer research and development include the optimization of lime slaking, application of cooling tower blowdown as makeup water, and investigation of alternate reagents and additives such as thiosorbic lime and lime or limestone with calcium chloride addition.

The first planned commercial application of dry injection technology has been announced by Public Service Company of Colorado (PSCC) for a 500 MWe unit. The system will use trona ore as the sorbent, and waste solids will be disposed of in a clay- and plastic-lined landfill.

EPRI has completed the 22 MWe dry injection demonstration tests at PSCC's Cameo Station. Test results showed 70 percent SO_2 removal for trona and nahcolite at reagent ratios of 1.3 and 0.8, respectively, and an inlet SO_2 concentration of about 450 ppmv. A recent cost study based on the Cameo results for a midwest site indicates that dry injection may be less expensive than spray drying, depending on reagent cost, coal sulfur content, and SO_2 removal requirements. A summary of these results and the results of other recent cost studies on dry SO_2 control systems is given in Section 4.0.

The electron-beam (E-beam) process, which is aimed at achieving simultaneous SO_2 and NO_x control, is still in an early developmental state. A pilot unit to test the E-beam/lime spray dryer version of the process has been constructed and testing began in early 1984. Construction of an E-beam/ammonia pilot plant was begun in late 1983.

2.2 SPRAY DRYER SYSTEMS

The following sections summarize recent commercial and R&D activities in the spray drying area. The commercial sales made to date and performance or compliance test results are highlighted in Section 2.2.1. Current or recently completed spray drying R&D programs and major results from these programs are discussed in Section 2.2.2. More detail on these commercial and R&D activities can be found in Section 3 of this report.

2.2.1 Commercial Activities

Tables 2-1 through 2-4 present the key features of the utility and industrial boiler spray drying FGD systems sold to date. Utility systems are covered in Tables 2-1 and 2-2, and Tables 2-3 and 2-4 provide similar information for the industrial boiler systems.

TABLE 2-1. SUMMARY OF UTILITY SPRAY DRYING SYSTEMS SOLD (MARCH 1984)

System Purchaser	Station/ Location	Size		Status	Vendor[a]
		Gross MWe	acfm		
Northern States Power Co.	Riverside, Units 6 and 7 (Minneapolis, MN)	110	640,000 @ 350°F	Operated for 15 months by vendor in 1981 and 1982. System now being operated by utility.	Joy/Niro
Pacific Power and Light	Jim Bridger, Unit 2, (Rock Springs, WY)	100	389,000 @ 230-240°F	Operated for 9 months by vendor. Testing completed; no plans for additional system operation.	Flakt
Otter Tail Power Co. (Montana-Dakota Utilities)[b]	Coyote, Unit 1 (Beulah, ND)	440	1,890,000 @ 285°F	Operational. Turned over to utility. Has achieved performance guarantees.	Rockwell/ Wheelabrator-Frye
United Power Association	Stanton, Unit 1A (Stanton, ND)	60	324,500 @ 232°F	Operational. Passed initial performance tests. Final stages of acceptance testing.	Cottrell Environmental/Komline-Sanderson
Marquette Board of Light and Power	Shiras, Unit 3 (Marquette, MI)	44	226,000 @ 227-265°F	Operational. Passed initial performance tests. Final stages of acceptance testing.	G.E. Environmental Services
Basin Electric Power Coop.	Laramie River, Unit 3 (Wheatland, WY)	575	2,300,000 @ 286°F	Operational. Has not yet met performance guarantees. Additional testing planned for early 1984.	Babcock and Wilcox
Colorado Ute Electric Assoc.	Craig, Unit 3	447	1,770,000 @ 245°F	Initial operation in early 1984	Babcock and Wilcox
Basin Electric Power Coop.	Antelope Valley, Unit 1 (Beulah, ND)	440	2,055,000 @ 318°F	Operational. Turned over to utility. Has achieved performance guarantees.	Joy/Niro
Basin Electric Power Coop.	Antelope Valley, Unit 2 (Beulah, ND)	440	2,055,000 @ 318°F	April 1985 start-up.	Joy/Niro

TABLE 2-1. SUMMARY OF UTILITY SPRAY DRYING SYSTEMS SOLD (MARCH 1984) (Continued)

System Purchaser	Station/ Location	Size		Status	Vendor[a]
		Gross MWe	acfm		
Tucson Electric Power	Springerville, Unit 1 (Springerville, AZ)	350	1,660,000 @ 256°F	June 1985 start-up.	Joy/Niro
Tucson Electric Power	Springerville, Unit 2 (Springerville, AZ)	350	1,660,000 @ 256°F	June 1987 start-up.	Joy/Niro
Platte River Power Authority	Rawhide, Unit 1 (Fort Collins, CO)	280	1,206,000 @ 270°F	In start-up. Performance tests in early 1984.	Joy/Niro
Sunflower Electric	Holcomb, Unit 1 (Holcomb, KS)	319	1,340,000 @ 260°F	Operational. Initial tests in January 1984.	Joy/Niro
Sierra Pacific Power	North Valmy (Valmy, NV)	270	1,200,000 @ 266°F	1985 start-up.	Rockwell
Grand River Dam Authority-State of Oklahoma	Pryor, Unit 2 (Pryor, OK)	520	1,850,000 @ 250-300°F	March 1985 start-up. August 1985 commercial operation.	Flakt
Northern States Power Company	Sherburne County, Unit 3 (Becker, MN)	860	3,930,000 @ 308°F	January 1988 start-up.	Joy/Niro
Cajun Electric	Oxbow, Unit 1 (Coushatta, LA)	563	2,600,000 @ 348°F	Projected for 1989, but need for system is being re-evaluated.	Joy/Niro
Central and South-western Services	Coleto Creek, Unit 2 (Corpus Christi, TX)	720	2,800,000 @ 270°F	April 1988 start-up.	Joy/Niro
Pacific Power and Light	Wyodak, Unit 1 (Gillette, WY)	330	2,260,000 @ 360°F	September 1986 start-up.	Joy/Niro

[a] Rockwell/Wheelabrator-Frye is no longer a joint venture, but both are offering spray drying systems.
Joy/Niro: Joy takes the lead in utility sales, while Niro takes the lead in industrial sales.
G.E. Environmental Services: Formerly Buell Emission Control Division, Envirotech Corporation. Spray dryer supplied by Anhydro A/S.
Cottrell Environmental Sciences supplies fabric filter. Komline-Sanderson supplies spray dryer.

[b] Station operator.

TABLE 2-2. DESIGN FEATURES SUMMARY FOR UTILITY COMMERCIAL SPRAY DRYER SYSTEMS[a]

		Design Coal Data			SO_2 Guarantee[d]			
System[b] (Vendor)	Description	Type	HHV[c] Ash	Sulfur	Removal	Outlet lb/10^6 Btu	Solids Recycle?	Solids Disposal
Riverside, Units 6 & 7 (Joy-Niro)	1 spray dryer with rotary atomizer; lime reagent; reverse-air fabric filter.	Montana subbituminous/coke	9,200 Btu/lb 8.9%	1.2% avg.	70%	1.2	Yes	Trucked to landfill.
Jim Bridger, Unit 2 (Flakt)	Reactor with 10 dual-fluid nozzle atomizers; ESP; testing both lime and soda ash.	Western subbituminous	11,600 Btu/lb; 10.0%	0.56% avg. 0.8% max.	Lime: 62-74% Soda ash: 74-86%	0.3	Variable with test; provisions exist.	Possible mine-mouth disposal.
Coyote, Unit 1 (Rockwell/ Wheelabrator-Frye)	4 parallel spray dryers, with 3 rotary atomizers each; initially will use soda ash reagent; reverse-air fabric filter.	North Dakota lignite	7,046 Btu/lb; 7.0%	0.78% avg.	70% for all fuels	1.2	No	Clay-lined landfill.
Stanton, Unit 1A (Cottrell/ Komline-Sanderson)	1 spray dryer with 3 rotary atomizers; lime reagent; reverse-air fabric filter.	North Dakota lignite	7,000 Btu/lb; 6.9%	0.77% avg. 1.94% max.	70% or 0.6 lb/10^6 Btu[e] (whichever is lower)		Under consideration.	Clay-lined pond water sluice.
Shiras, Unit 3 (G.E. Environmental Services)	1 spray dryer with a single rotary atomizer; lime reagent; reverse-air fabric filter; 3 percent hot gas bypass around dryer.	Western subbituminous	8,645 Btu/lb; 10.25%	1.5% max.	80% design removal	0.94	Yes	Landfill.
Laramie River, Unit 3 (Babcock and Wilcox)	4 parallel reactors (1 spare) with 12 "y-jet" nozzle atomizers each; lime reagent; each reactor followed by an ESP; 5 percent gas bypass around dryer.	Wyoming subbituminous	8,140 Btu/lb; 8%	0.54% avg; 0.81% max.	82% for avg; 90% for max.	0.20	Yes	Lined landfill.
Craig, Unit 3 (Babcock and Wilcox)	4 parallel reactors (1 spare) with 12 "y-jet" nozzle atomizers each; lime reagent; reverse-air fabric filter.	Western subbituminous	8,950 Btu/lb; 14%	0.7%	87%	0.20	Yes	Dry landfill.
Antelope Valley, Unit 1 (Joy/Niro)	5 parallel spray dryers (1 spare) single rotary atomizer per dryer; lime reagent; reverse-air fabric filter; 3.2 percent hot gas bypass around dryer.	North Dakota lignite	6,600 Btu/lb; 7.8%	0.68% avg. 1.22% max.	62% for avg. 78% for max.	0.78	Yes	Wetted transport to lined landfill.

TABLE 2-2. DESIGN FEATURES SUMMARY FOR UTILITY COMMERCIAL SPRAY DRYER SYSTEMS[a] (Continued)

		Design Coal Data			SO_2 Guarantee[d]			
System[b] (Vendor)	Description	Type	HHV[c] Ash	Sulfur	Removal	Outlet lb/10^6 Btu	Solids Recycle?	Solids Disposal
Antelope Valley, Unit 2 (Joy/Niro)	Same as Antelope 1 above, except no bypass	Same as Antelope 1			89% for max.	0.39	Yes	Same as Antelope 1.
Springerville, Unit 1 (Joy/Niro)	3 parallel spray dryers (1 spare); single rotary atomizer per dryer; lime reagent; reverse-air fabric filter; 17.5 percent gas bypass around dryer.	New Mexico subbituminous	8,500 Btu/lb; 20%	0.69% avg.	61%	0.6	Yes	Natural clay-lined landfill.
Springerville, Unit 2 (Joy/Niro)	Same as Springerville 1	Same as Springerville 1			Same as Springerville 1		Yes	Same as Springerville 1.
Rawhide, Unit 1 (Joy/Niro)	3 parallel spray dryers (1 spare) single rotary atomizer per dryer; lime reagent; reverse-air fabric filter; 10 percent gas bypass around dryer.	Western subbituminous	8,500 Btu/lb; 6.0%	0.3% avg. 0.44% max.	80%	0.18	Yes	Dry landfill.
Holcomb, Unit 1 (Joy/Niro)	3 parallel spray dryers (1 spare); single rotary atomizer per dryer; lime reagent; reverse-air fabric filter.	Wyoming subbituminous	8,313 Btu/lb; 5.6%	0.34% avg.	80%	0.27	Yes	Landfill with fixation.
North Valmy (Rockwell)	3 parallel spray dryers (no spare); 3 rotary atomizers per dryer; lime reagent; reverse-air fabric filter, gas bypass.	Western subbituminous	8,000 Btu/lb; 11 to 32%	0.4 to 1.0	70% for all coal	0.6	Yes	Possible mine-mouth disposal.
Pryor, Unit 2 (Flakt)	4 reactors in parallel, (1 spare) each with 3 rotary atomizers; lime reagent; ESPs, gas bypass.	Western subbitum-	8,000-9,000 Btu/lb; 7%	0.4 to 1.5%	85% for all coal	NR	Provision will exist.	Landfill.
Sherburne County, Unit 3 (Joy/Niro)	8 parallel spray dryers (1 spare); single rotary atomizer per dryer; lime reagent; reverse-air fabric filter; gas bypass.	Sarpy Creek subbituminous	8,300 Btu/lb; 10.8%	0.9% avg. 2.3% max.	70%	0.6	Yes	NR

TABLE 2-2. DESIGN FEATURES SUMMARY FOR UTILITY COMMERCIAL SPRAY DRYER SYSTEMS[a] (Continued)

		Design Coal Data			SO_2 Guarantee[d]			
System[b] (Vendor)	Description	Type	HHV[c] Ash	Sulfur	Removal	Outlet lb/10^6 Btu	Solids Recycle?	Solids Disposal
Oxbow, Unit 1 (Joy/Niro)	5 parallel spray dryers (no spare); single rotary atomizer per dryer; lime reagent; reverse-air fabric filter; gas bypass.	Louisiana lignite	6,150 Btu/lb; 21.1%	0.93% avg.	80%	0.6	Yes	Landfill.
Coleto Creek Unit 2, (Joy/Niro)	4 parallel spray dryers (1 spare); single rotary atomizer per dryer; lime reagent; electrostatic precipitators; gas bypass.	Colorado subbituminous	NR	0.4% avg.	70%	0.3	Yes	NR
Wyodak, Unit 1 (Joy/Niro)	3 parallel spray dryers (no spare); single rotary atomizer per dryer.	Wyoming subbituminous	8,250 Btu/lb; 5%	0.4% avg.	75%	0.5	Yes	NR

[a] Some of the information contained in the table, particularly on gas bypass percentage, outlet SO_2 levels, and solids disposal was obtained from a recent report on the status of utility spray drying applications - Reference 1.

[b] Referred to by generating station name as given in Table 2-1.

[c] HHV = high heating value, HHV; % ash reported as average for the design coal.

[d] Where guarantee information was not available, design values are reported.

[e] PSD permit for Holcomb based on 1 percent S coal at 7800 Btu and a 0.48 lb $SO_2/10^6$ Btu outlet emission limit (corresponds to about 91% removal for maximum sulfur coal).

[f] Designed for wide range of coal types.

[g] NR = Not reported.

TABLE 2-3. SUMMARY OF INDUSTRIAL BOILER SPRAY DRYING SYSTEMS SOLD (MARCH 1984)

System Purchaser/Location	Size acfm	Size lb steam/hr	Status	Vendor[a]
Argonne National Laboratory Argonne, IL	75,000 @ 300°F	170,000	Operational. Turned over to system purchaser. Has achieved removal guarantees.	Niro/Joy
Strathmore Paper Company Woronoco, MA	40,000 acfm @ 330°F	85,000	Operational. Turned over to system purchaser. Has achieved removal guarantees.	Mikropul/Koch
Celanese Fibers Company Cumberland, MD	65,000 acfm @ 350-370°F	110,000	Operational. Turned over to system purchaser. Has achieved removal guarantees.	Rockwell/ Wheelabrator-Frye
Container Corporation Philadelphia, PA	94,300 acfm @ 350°F	170,000	Operational. Turned over to system purchaser. Has achieved removal guarantees.	Ecolaire, Inc.
University of Minnesota; Units 1 & 2 Minneapolis, MN	120,000 acfm each @ 375°F	40 MWe[b] each	One unit operational. Second start-up in Spring 1984. Initial testing in mid-1984.	Flakt[c]
Austell Box Board Co. Austell, Georgia	110,000 acfm @ 350°F	250,000	Operational. Passed compliance tests. Final stages of acceptance testing.	Wheelabrator-Frye
General Motors Buick Division Flint, MI	172,500 acfm @ 305°F	450,000	Operational. Initial testing in January 1984.	Niro/Joy
Fairchild Air Force Base; Units 1, 2, and 3 Spokane, WA	51,250 acfm each @ 320°F	110,000 each	Operational. Initial testing in Spring 1984.	Niro/Joy
Puget Sound Naval Shipyard; Units 1, 2, and 3 Bremerton, WA	67,000 acfm each @ 350°F	140,000 each	Start-up scheduled for late 1987.	General Electric

TABLE 2-3. SUMMARY OF INDUSTRIAL BOILER SPRAY DRYING SYSTEMS SOLD (MARCH 1984) (Continued)

System Purchaser/Location	Size acfm	Size lb steam/hr	Status	Vendor[a]
Malmstrom Air Force Base; Units 1, 2, and 3 Great Falls, MT	50,000 acfm each @ 350°F	90,000 each hot water	Start-up scheduled for Spring 1985.	Niro/Joy
Griffiss Air Force Base; Units 1, 2, 3, and 4 Rome, NY	50,000 acfm each @ 350°F	90,000 each	Start-up scheduled for Fall 1984.	Ecolaire

[a] Niro/Joy: Niro takes the lead in industrial sales, while Joy takes the lead in utility sales.
MikroPul/Koch: MikroPul originally sold the Strathmore system, but now operates with Koch Engineering in a joint venture for future spray dryer sales.
Rockwell/Wheelabrator-Frye: (see note, Table 2-1).

[b] Part of cogeneration system.

[c] Originally sold by Kennecott Development Co., which was purchased by Flakt in early 1982.

TABLE 2-4. DESIGN FEATURES SUMMARY FOR INDUSTRIAL BOILER SPRAY DRYING SYSTEMS

		Design Coal Data			SO_2 Guarantee[c]			
System[a] (Vendor)	Description	Type	HHV[b] Ash	Sulfur	Removal	Outlet($lb/10^6 Btu$)	Solids Recycle?	Solids Disposal
Argonne National Lab (Niro/Joy)	One spray dryer with single rotary atomizer; lime reagent; pulse-jet fabric filter.	Illinois bituminous	11,800 Btu/lb 8.0%	3.5%	78.7%	1.2	Yes	On-site landfill.
Strathmore Paper Co. (Mikropul/Koch)	One spray dryer with four nozzle atomizers; lime reagent; pulse-jet fabric fiber.	Eastern bituminous	13,000 Btu/lb NR[d]	2.3 to 3%	75%	1.2	No	Trucked to off-site land-fill.
Celanese Fiber Co. (Rockwell/ Wheelabrator-Frye)	One spray dryer with single rotary atomizer; lime reagent; pulse-jet fabric filter; warm gas bypass.	Eastern subbituminous	NR	2.0% maximum	70% for 1% S coal; 86% for 2% S coal	70 lb/hr SO_2 outlet	No	Trucked to off-site landfill.
Container Corp. (Ecolaire)	One spray dryer with single rotary atomizer; lime reagent; pulse-jet fabric filter.	Eastern subbituminous	12,500 Btu/lb NR	0.6%	Design removal of 90%	0.6	Yes	Trucked to off-site landfill.
University of Minnesota; (Flakt) Units 1, 2.	Two spray dryers, each with a single rotary atomizer; lime reagent; reverse-air fabric filter.	Subbituminous	NR	0.6 to 0.7%	70%[e]	NR	No	NR
Austell Box Board Co. (Wheelabrator-Frye)	One spray dryer with 12 nozzle atomizers; lime reagent; pulse-jet fabric filter; warm gas bypass.	Bituminous	12,000 Btu/lb 9 to 15%	1.5 to 2.5%	Varies with sulfur content	1.2	No	NR
General Motors (Niro/Joy)	One spray dryer with single rotary atomizer; lime reagent; pulse-jet fabric filter.	Indiana bituminous	NR	1-3%	70 to 90%	1.2	Yes	Trucked to off-site landfill.
Fairchild AFB; Units 1, 2, 3 (Niro/Joy)	Three spray dryers (one per unit), each with a single rotary atomizer; lime reagent; three pulse-jet fabric filters (one per unit).	Western subbituminous	NR	1%	85%	NR	Yes	Trucked to off-site landfill.

TABLE 2-4. DESIGN FEATURES SUMMARY FOR INDUSTRIAL BOILER SPRAY DRYING SYSTEMS (Continued)

		Design Coal Data			SO_2 Guarantee[c]			
System[a] (Vendor)	Description	Type	HHV[b] Ash	Sulfur	Removal	Outlet(lb/10^6Btu)	Solids Recycle?	Solids Disposal
Puget Sound Naval Shipyard; Units 1, 2, 3 (General Electric)	Three spray dryers (one per unit), each with a single rotary atomizer; lime reagent; reverse-air fabric filter.	Subbituminous	NR	1.6% maximum	84%	NR	No	NR
Malmstrom AFB; Units 1, 2, 3 (Niro/Joy)	Three spray dryers (one per unit), each with a single rotary atomizer; lime reagent; three reverse-air fabric filters (one per unit).	Western subbituminous	9,500 Btu/lb 8.5%	1%	85%	NR	Yes	NR
Griffiss AFB; Units 1, 2, 3, 4 (Ecolaire)	Four spray dryers (one per unit), each with a single rotary atomizer; lime reagent; four pulse-jet fabric filters (one per unit).	Pennsylvania bituminous	12,070 Btu/lb 9.45%	3%	85%	0.71	Yes	NR

[a] Referred to by system purchaser as shown in Table 2-3.

[b] HHV = high heating value, Btu/lb; HHV and % ash reported as average for the design coal.

[c] Where guarantee information not available, design values are reported.

[d] NR = not reported.

[e] At a reagent ratio of 1.0.

Utility Systems

Table 2-1 shows the 18 utility systems sold to date. The applications range in size from 44 to 860 MWe (gross electrical output) and total about 7,150 MWe in FGD system capacity. The retrofit system at the Northern States Power Company (NSP) Riverside Station was operated as a demonstration unit by the system vendor, Joy/Niro, for 9 months in 1981 and approximately 6 months in 1982. The Riverside system is now being operated by NSP. A second retrofit system at the Pacific Power and Light Company Jim Bridger Station was operated by Flakt as a demonstration unit for 9 months in 1982. This system was shut down in October 1982, and no additional operation of the unit is planned.

Seven commercial utility spray drying systems are now operational. Of these the sodium-based system at Coyote Station was turned over to Montana-Dakota Utilities for operation following final acceptance and compliance testing in August 1982. Earlier test results reported for this system showed 70 percent SO_2 removal at a soda ash utilization of 75 percent and an approach to saturation of 65°F.

Three of the operational utility systems (Stanton, Shiras, and Antelope Valley I) met performance guarantees in mid- to late-1983. Performance data for these systems are summarized later in this section and are also discussed in Section 3.0. The Antelope Valley system has been turned over to Basin Electric for commercial operation. Initial performance testing at Sunflower Electric's Holcomb Station is scheduled for January 1984.

One utility system (Rawhide Unit 1) is in the initial startup stage, and one other system (Craig Unit 3) is scheduled for startup by the end of 1984.

Two new utility systems were sold since January 1983. Both systems were awarded to Joy/Niro. One contract was for a lime-based spray dryer/ESP system to serve a new 710 MWe unit at Central and Southwestern Services' Coleto Creek Station. Six parallel spray dryers, each with a rotary atomizer, will treat 2,800,000 acfm of flue gas from a boiler firing a 0.4 percent sulfur subbituminous coal. The second system is for an existing 330 MWe boiler at Pacific Power and Light's Wyodak Station. Three parallel lime-based spray dryers, each with a rotary atomizer, will treat flue gas from a boiler firing a 0.4 percent sulfur subbituminous coal. An existing ESP will be used for particulate collection. Both of the new utility systems will use warm gas bypass and solids recycle.

Table 2-2 summarizes the design features of the utility spray drying systems. All are designed for low to moderate sulfur coal (1.5 percent sulfur or less), except for a maximum design value of 1.94 percent sulfur at United Power's Stanton Station. SO_2 removal guarantees range from 61 to 91 percent. Lime will be used in all of the systems except Coyote. All but three of the systems will use a fabric filter for solids collection, with the exceptions using an ESP. Warm or hot gas bypass is used on a site-specific basis, and solids recycle is included in all but one of the 15 lime-based systems. Benefits of solids recycle include (1) increasing lime utilization, (2) providing an opportunity for utilization of fly ash alkalinity, and (3) improving spray dryer operability.

The dry product solids/fly ash mixtures generated by the spray drying systems will be disposed of in landfills at most of the utility locations. Available information indicates that for some of the landfill operations the solids will be wetted before transfer to the landfill to reduce dusting problems. Most of the vendors' utility system contracts do not include responsibility for waste disposal operations. An exception is Joy/Niro's contract with Sunflower Electric, which includes designing and supplying equipment for a fixated solids disposal process.

Industrial Boilers

Table 2-3 shows the 21 industrial boiler commercial spray drying units sold to date. (A few vendors have also sold spray drying system for incinerators or kilns, but these applications are not covered in detail in this report.) Table 2-3 shows that the industrial systems range in size from one 85,000 lb steam/hr boiler at Strathmore Paper Company's Woronoco, Massachusetts plant to two 40 MWe boilers that are part of a cogeneration system at the University of Minnesota in Minneapolis.

Ten of the industrial boiler units are operational. Four units have achieved performance guarantees and are being operated by their respective purchasers. These include the Celanese, Strathmore, Argonne, and Container systems. A fifth unit (Austell Box Board) has passed compliance tests but has not yet been turned over to the system purchaser. The remaining five units have only recently become operational, and performance and compliance testing is planned for early 1984.

Ten new industrial units were sold since late 1982 for three Federal government installations (one Navy and two Air Force). Each unit will consist of a lime-based spray dryer equipped with a single rotary atomizer and followed by a fabric filter for particulate collection. Six of the units will use reverse-air fabric filters and the other four will use pulse-jet fabric filters. Seven units will use solids recycle. The new industrial units were sold by General Electric for the Puget Sound Naval Shipyard (three boilers, 1.6 percent maximum sulfur coal), Niro/Joy for the Malmstrom Air Force Base (three boilers, 1 percent sulfur coal), and Ecolaire for the Griffiss Air Force Base (four boilers, 3 percent sulfur coal).

A relatively new area of application for spray drying technology is for municipal waste incinerators. At least two vendors are conducting research and development on the use of spray drying to control SO_2, HCl, and HF emissions from these incinerators, and Combustion Engineering has sold a 40 to 50 MWe equivalent spray drying/fabric filter system for this application.

Table 2-4 summarizes the design features of the industrial boiler units. The design coal sulfur contents in the industrial applications, all of which will use lime, range from 0.6 to 3.5 percent. Sulfur dioxide removal guarantees range from 70 to 90 percent, with at least eight units designed to meet a 1.2 lb SO_2/million Btu (heat input) or lower emission limit. Solids recycle will be used on all except eight of the industrial units, and only two units will use warm gas bypass. Thirteen units will have pulse-jet fabric filters, and the others will use reverse-air. Pulse-jet fabric filters are usually selected over reverse-air filters up to a certain size (about 100,000 acfm) because pulse-jet filters operate at higher air-to-cloth ratios (less bags). Above the cutoff, which is a function of site-specific factors, pressure drop costs offset the savings associated with the higher air-to-cloth ratios of pulse-jet designs. The selection of reverse-air fabric filters for the new 50,000 acfm units at Malmstrom Air Force Base and the new 67,000 acfm units at Puget Sound Naval Shipyard were probably based on vendor or customer preference instead of economics.

Off-site land disposal of the waste solids will be used in most of the industrial applications since there is typically little land available for on-site disposal.

Spray Drying System Vendors

The firms currently offering utility and/or industrial boiler spray drying systems are listed in Table 2-5. As shown in Table 2-5, a number of the vendors offer both nozzle and rotary atomizers, with nozzle atomizers preferred for small industrial systems and rotary atomizers preferred for large industrial and utility systems. Three vendors, Flakt, Cottrell, and Rockwell, offer multiple rotary atomizer per dry designs for utility systems. Vertical flow dryers are still the most common design, although Babcock and Wilcox offers a horizontal flow dryer design.

Performance Data

Table 2-6 summarizes recently published compliance test data for operating full-scale spray drying systems. Recently reported data on SO_2 removal as a function of reagent ratio for several different lime-based systems are shown in Figure 2-1. Process conditions for data in Figure 2-1 are given in Table 2-7. Data reported for lime-based systems in the previous status report are shown for comparison in Figure 2-2 with the corresponding process conditions given in Table 2-8.

TABLE 2-5. FIRMS OFFERING A COMMERCIAL SPRAY DRYING FGD SYSTEM

Firm or Team of Firms	Design Features[a] Spray Dryer[b]	Design Features[a] Atomization	Number of Units Sold in U.S. Utility	Number of Units Sold in U.S. Industrial[c]
Babcock and Wilcox (B&W)	Horizontal dryer with hoppers for solids collection.	12 "Y-jet" air-atomized nozzles for each full-size reactor	2	Does not plan to bid.
Combustion Engineering, Inc.	Two-point discharge vertical dryer.	Multiple (externally-mixed) sonic nozzle atomizers per dryer	None	None
Cottrell Enviromental Sciences, Inc. and Komline-Sanderson, Inc.	Two-point discharge vertical dryer.	Multiple (3) rotary atomizers per dryer. Nozzle atomizers for sodium-based systems.	1	None
Ecolaire, Inc.	Two-point discharge vertical dryer.	Single rotary atomizer per dryer. Have tested nozzle atomizers.	None	5
Flakt, Inc.	Two-point discharge vertical dryer.	Multiple atomizers per dryer. Three rotary per dryer for full-scale utility module.	1	2
G.E. Environmental Services	Two-point discharge vertical dryer.	Single rotary atomizer per dryer.	1	3
Joy Manufacturing Company and Niro Atomizer, Inc.	Two-point discharge vertical dryer with central gas disperser.	Single rotary atomizer per dryer.	10	8
Mikropul, Inc. and Koch Engineering, Inc.	Two-point discharge vertical dryer with "proprietary" internals.	Multiple air-atomized nozzles per dryer. Investigating rotary atomizers.	None	1
Rockwell International	Single-point discharge vertical dryer.	Multiple (3) rotary atomizers per dryer for utility. Single rotary atomizer per dryer for industrial.	2[d]	1[e]
Wheelabrator-Frye, Inc.	Vertical dryer with nozzle atomizers or vertical with rotary atomizers.	Multiple air-atomized nozzles for industrial. Single rotary atomizer per dryer for utility or large industrial.	1[e]	2[d]

[a] Based primarily on commercial systems sold to date and reported R&D activities. Vendors may offer other design features.

[b] Two-point discharge dryers have bottom discharge for solids that drop out in dryer.

[c] Note that industrial systems often have multiple spray dryer/fabric filter units at a single installation.

[d] One sold by Rockwell/Wheelabrator-Frye joint venture, other sold independently.

[e] Sold by Rockwell/Wheelabrator joint venture.

TABLE 2-6. COMPLIANCE TEST RESULTS FOR SPRAY DRYING SYSTEMS

System Vendor	Compliance Test Data					Comments
Austell Box Board/ Wheelabrator-Frye	Test No.	Outlet SO_2 (ppmv)	Outlet SO_2 lb/10^6 Btu	SO_2 Removal[a] (%)		
	1	368	0.89	73		Lime reagent, no recycle, 1.5 to 2.5% S coal. EPA Method 6 tests. Near 100% boiler load for all tests.
	2	434	1.05	68		
	3	345	0.82	75		
	4	324	0.77	77		
	5	340	0.80	76		
	6	319	0.75	77		
	avg.	355	0.85	74		
Container Corporation/ Ecolaire	Test No.	Outlet SO_2 (ppmv)	Outlet SO_2 lb/10^6 Btu	SO_2 Removal[b] (%)		
	1	13.0	0.040	97		Lime reagent, no recycle, 0.6% S coal. EPA Method 6 tests.
	2	9.0	0.029	98		
	3	9.0	0.031	97		
	avg.	10.0	0.033	97		
Shiras Station/ G.E. Environmental	Test No.	Outlet SO_2 (ppmv)	SO_2 Removal (%)			
	avg.[c]	40.0	87.3			Lime reagent, no recycle, 0.5% S coal. Average of three EPA Method 6 tests.
Stanton Station/ Cottrell Environmental	Test No.	Outlet SO_2 lb/10^6 Btu	SO_2 Removal (%)			
	avg.[d]	0.45	69.6			Lime reagent, no recycle, 0.7% S coal. Average of six EPA Method 6 tests.
Antelope Valley Station/ Joy/Niro	Test No.	Inlet SO_2 (ppmv)	Outlet SO_2 (ppmv)	Outlet SO_2 lb/10^6 Btu	SO_2 Removal (%)	
	avg.[e]	668	171	0.46	74	Lime reagent, solids recycle, 0.7% S coal. EPA Method 6 tests.

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[a] Based on inlet SO_2 mass rate of 3.33 lb/10^6 Btu as calculated from coal properties.
[b] Based on inlet SO_2 mass rate of 1.2 lb/10^6 Btu as calculated from coal properties.
[c] Average of three tests.
[d] Average of six tests.
[e] Number of tests not reported.

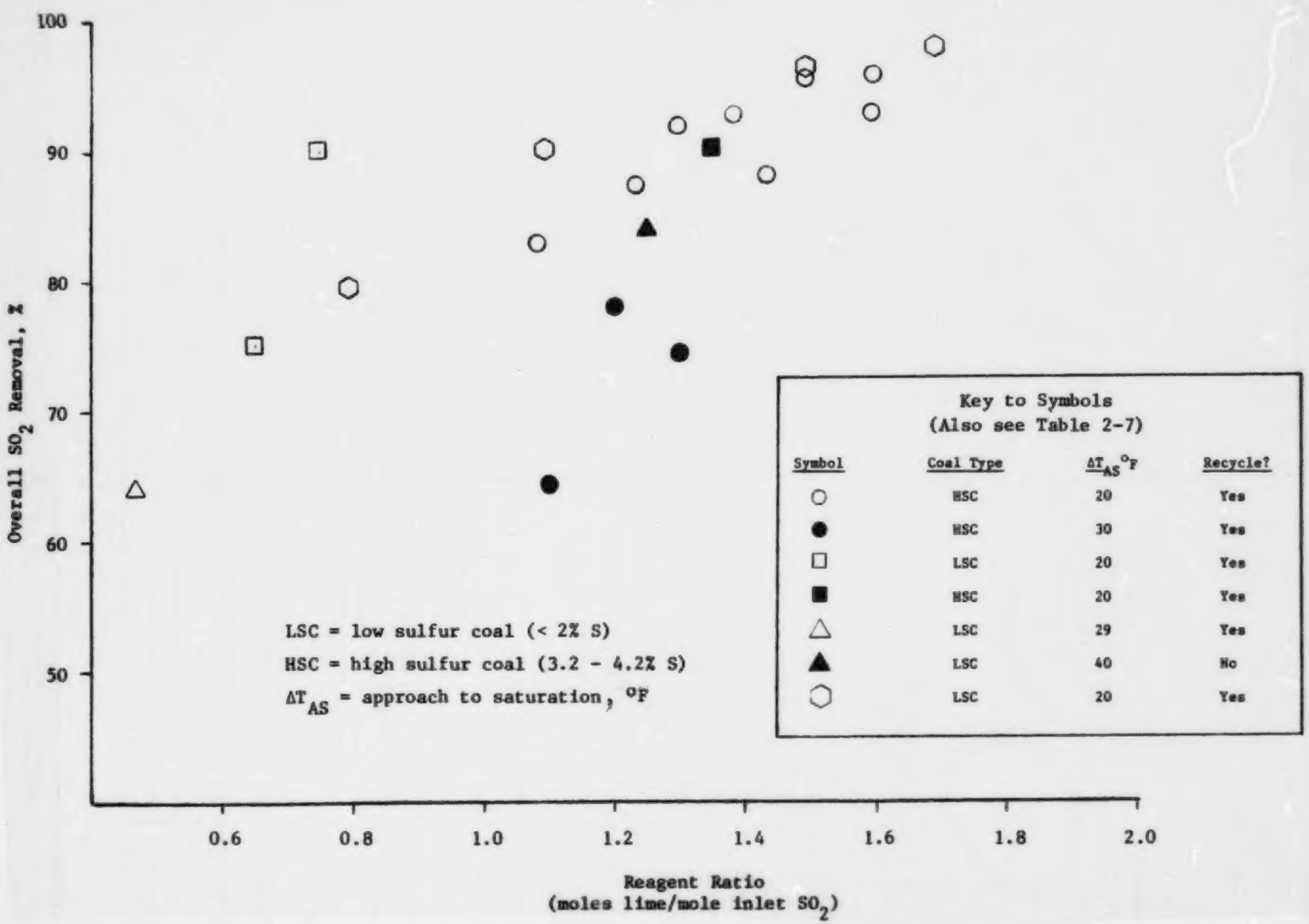


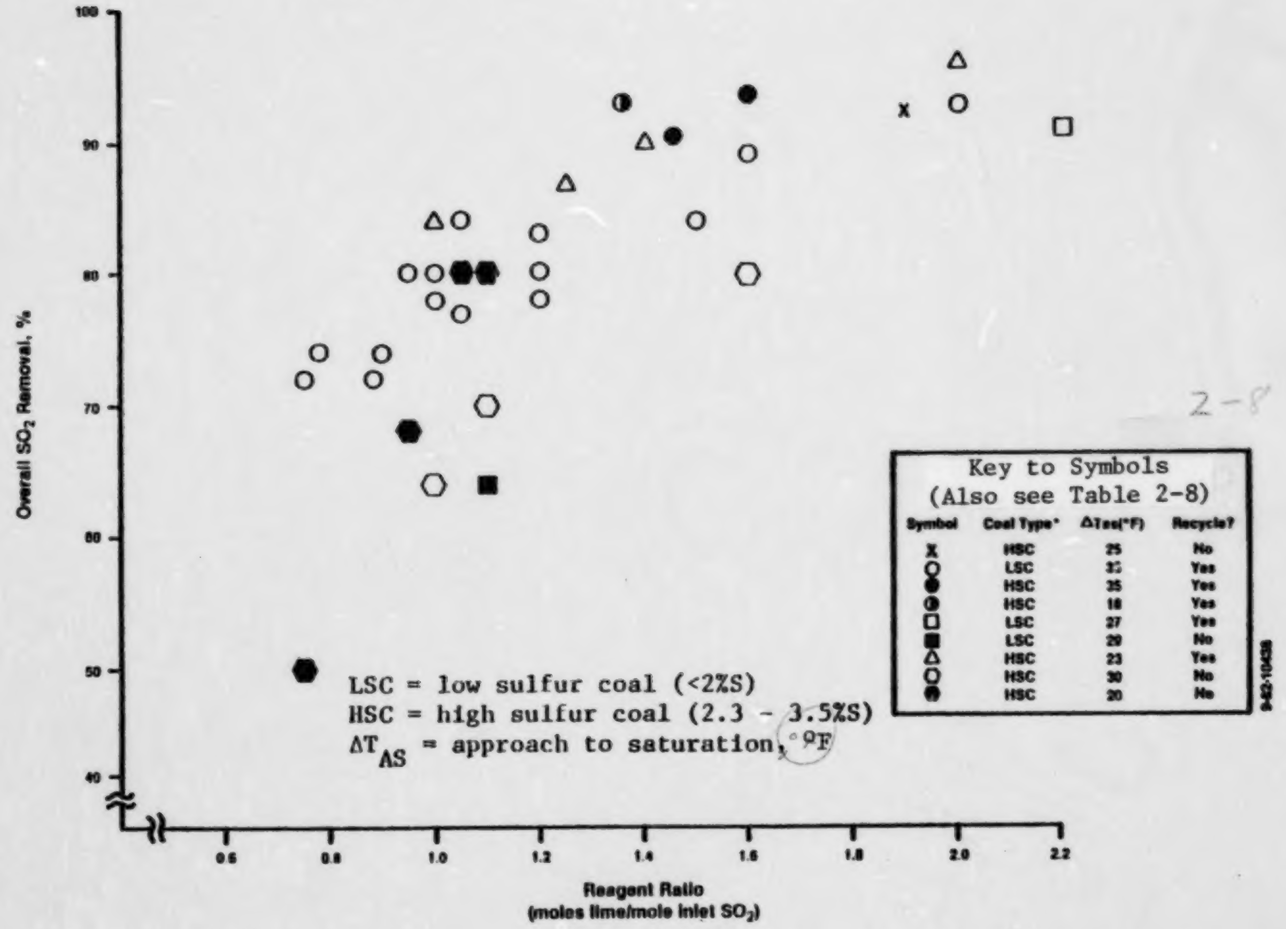
Figure 2-1. Comparison of overall SO_2 removal data reported for various lime-based spray dryer FGD systems in 1983.

TABLE 2-7. PROCESS CONDITIONS FOR DATA SHOWN IN FIGURE 2-1

		Process Description					
Symbol from Figure 2-1	System Description[a]	Coal Type	%S	Inlet SO_2 (ppmv)	Inlet Gas Temp (°F)	ΔT_{AS}[b] (°F)	Recycle?
○	Argonne Lab: 170,000 lb steam/hr boiler; 75,000 acfm; 25-ft diameter dryer; rotary atomizer; fabric filter.	West Virginia bituminous	4.2	2,500	320	20	Yes
●	Argonne Lab	West Virginia bituminous	4.2	2,500	320	30	Yes
□	Riverside Station: 110 MWe unit; 680,000 acfm; 46-ft diameter dryer; rotary atomizer; fabric filter.	Sarpy Creek coal blended with petroleum coke	1.2	900	∿ 315	20	Yes
■	Riverside Station	Illinois bituminous	3.4	1,900	∿ 315	20	Yes
△	Antelope Valley Station: 435 MWe unit; 2,055,000 acfm; five 46-ft diameter dryers; rotary atomizer; fabric filter.	North Dakota lignite	0.7	655	314	29	Yes
▲	Shiras Station: 44 MWe unit; 226,000 acfm; 36-ft diameter dryer; rotary atomizer; fabric filter.	Western subbituminous	0.5	∿ 500	310-330	40	No
⬡	EPRI: 8,000 acfm pilot unit; 10-ft diameter dryer; rotary atomizer; fabric filter.	Western subbituminous	∿ 0.4	400	260-280	20	Yes

[a] Argonne system is a Joy/Niro design. See Sections 3.4 and 3.11.
Riverside system is a Joy/Niro design. See Sections 3.8 and 3.11.
Antelope Valley is a Joy/Niro design. See Section 3.11.
Shiras Station is a General Electric design. See Section 3.10.
See Section 3.7 for description of EPRI system.

[b] ΔT_{AS} = approach to saturation temperature



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2-2

Figure 2-2. Comparison of overall SO_2 removal data for various lime-based spray dryer FGD systems.

TABLE 2-8. PROCESS CONDITIONS FOR DATA SHOWN IN FIGURE 2-2

				Process Conditions			
Symbol from Figure 2-2	System Description	Coal Type	%S	Inlet SO_2 (ppmv)	Inlet Gas Temp (°F)	ΔT_{AS} (°F)	Recycle?
○	Riverside Station: 110 MWe unit; 680,000 acfm; 46-ft diameter dryer; rotary atomizer; fabric filter	Colstrip coal blended with petroleum coke	1.2	850-1,000	280-315	35	Yes
●	Riverside	Illinois bituminous	3.5	~ 2,000	316-331	32-35	Yes
◐	Riverside	Illinois bituminous	3.5	~ 2,000	~ 315	18	Yes
□	Jim Bridger Station; 100 MWe unit; 389,000 acfm; 10 dual-fluid nozzle atomizers; ESP	Western sub-bituminous	~ 0.6	NR	229	27	Yes
■	Jim Bridger	Western sub-bituminous	~ 0.6	NR	238	29	No
×	Strathmore: 85,000 lb steam/hr; 40,000 acfm; 14.5-ft diameter dryer; rotary atomizer; fabric filter	Eastern bituminous	3.8	~ 2,000	~ 330	25	No
△	Argonne Lab: 170,000 lb steam/hr boiler; 75,000 acfm; 25-ft diameter dryer; rotary atomizer; fabric filter.	Illinois bituminous	3.0	~ 2,200	~ 300	23	Yes
⬡	PETC: 500 lb/hr pulverized coal furnace; 7-ft diameter dryer; rotary atomizer; fabric filter	West Virginia bituminous	3.1	~ 2,200	~ 400	30	No
⬢	PETC	West Virginia bituminous	3.1	NR	NR	20	No

Future Commerical Activities

Currently only one utility is reported to be considering dry FGD for a new plant (2). Nebraska Public Power is considering dry FGD for a 650 MWe unit to fire a 0.4 percent sulfur coal. Startup of the system is scheduled for 1986.

2.2.2 Research and Development Activities

Table 2-9 shows the status of three recent spray drying research and development programs. Results from all three programs were presented at the EPA/EPRI FGD Symposium in November 1983.

As part of the EPA/EPRI-funded processes testing at the Riverside Station, high sulfur coal (3.4 percent S) tests were conducted with and without calcium chloride addition for lime utilization enhancement. Results of the high sulfur coal tests without calcium chloride addition showed 90 percent SO_2 removal at a reagent ratio of 1.3 to 1.4 and an approach to saturation of 20°F. With calcium chloride addition, lime requirements for the high sulfur coal were reduced by 20 to 25 percent. Other tests conducted at the Riverside Station involved operation at 75 and 90 percent SO_2 removal with low sulfur coal. Details on the results from this program can be found in Section 3.7.

Testing with high sulfur coal has also been conducted under DOE funding at B&W's Alliance Research Center and on the spray drying system at Argonne National Laboratory. In addition, preliminary results have been reported from pilot spray drying studies being conducted by Cottrell Environmental and Rockwell, each under joint funding agreements with TVA. Results from these four programs showed that, at a relatively close approach to saturation of 20°F, reagent ratios of at least 1.3 are required to achieve 90 percent SO_2 removal on high sulfur coals (2.5 to 4 percent S).

The EPRI-funded pilot testing conducted to date has focused on low to moderate sulfur operation. EPRI found that both spray dryer operability and SO_2 removal are improved with solids recycle operation. Also, two simulated cooling tower blowdown streams were found to be suitable for spray dryer system makeup water (see Section 3.7).

In general, these and earlier R&D programs have indicated that the major process variables influencing SO_2 removal in the spray dryer system are: (1) fresh reagent ratio, (2) approach to saturation at the dryer outlet, and (3) recycle ratio. However, optimization of gas/liquid contact, atomization quality, and gas residence time in the dryer have been shown to be important not only from an SO_2 removal standpoint, but also in ensuring trouble-free spray dryer operation. Spray dryer operability has also been shown to improve with increased weight percent solids (up to 35 or 40 percent) in the atomizer feed slurry.

TABLE 2-9. MAJOR CURRENT SPRAY DRYING R&D ACTIVITIES

Vendor, Agency, or Industry Group	Size	Location	Comments
Electric Power Research Institute (EPRI)	255 m^3/min^a (8,000 cfm)	Arapahoe pilot plant; Denver, CO.	Test program began in March 1982. Testing planned through Summer 1984.
EPA/EPRI	110 MWe	Riverside Station, Northern States Power. Minneapolis, MN.	Ten weeks of testing completed in October 1983. Final report in preparation.
DOE/Babcock and Wilcox	25 m^3/min (900 scfm)	B&W Alliance Laboratory. Alliance, OH.	High sulfur testing completed in mid-1983. Final report in preparation.

[a] Actual flue gas conditions.

Other variables that have been shown to impact SO_2 removal in the spray drying system are: (1) inlet SO_2 concentration, (2) temperature drop across the spray dryer, (3) slaking water composition, and (4) lime reactivity.

Results from R&D programs such as the ones discussed above, combined with operating data from full-scale commercial systems and demonstration programs, have provided better definition of the important spray dryer FGD design and operating parameters. However, there remain a number of areas in which consistent, well-characterized data have not been published. Basically, there are six major areas of current technical interest:

- atomization,
- the roles of fly ash and recycle solids,
- high sulfur coal applications,
- less expensive reagents than lime,
- particulate collection and SO_2 removal in ESP's, and
- utilization schemes for solid waste.

Continued research and development in the atomization area is focused primarily on improving atomizer designs for FGD applications and comparing the performance of nozzle and rotary atomizers. Although few results of these efforts have been published, several vendors have reported successful development of improved nozzle atomizer designs, and others are developing rotary atomizers with increased capacity to allow for higher slurry flowrates. At least two vendors are investigating the use of nozzle atomizers for smaller industrial applications (e.g., less than 250,000 acfm), but would favor rotary atomizers for utility and large industrial systems. The two types of atomizers are generally compared on the following bases:

- droplet size produced,
- power requirements,
- mechanical complexity,
- spray patterns produced,
- abrasion and/or plugging experiences, and
- ability to handle slurry flows associated with varying boiler load.

The improvements in SO_2 removal and lime utilization resulting from solids recycle have been well documented by R&D activities over the past several years. These improvements result from the opportunity for the use of unused reagent and fly ash alkalinity in the recycle solids. Recycle will likely prove necessary for economical operation of spray drying FGD for high sulfur coal applications. The recent R&D activities in the area of solids recycle have not yet provided, however, a fundamental understanding of the role of fly ash in the spray drying process. The mechanisms by which fly ash contributes to SO_2 removal, by either providing alkalinity or surface catalysts, still remains to be defined. Another area potentially requiring further investigation is the manner in which recycle solids should be added to the system. No conclusive data have yet been published showing whether separate slurrying or direct addition to the fresh feed tank provides optimum benefit from recycle.

Recent data from high sulfur coal applications (such as Riverside, Argonne, and B&W's Alliance Research Center) have provided information on the reagent ratios, approach to saturation, and recycle ratios required to achieve 90 percent or greater SO_2 removals at 2,000 to 3,000 ppm inlet SO_2. R&D activities for high sulfur coal applications continue to focus on optimization of atomization, spray dryer operation, solids recycle, and additives to reduce fresh reagent requirements. Reducing reagent requirements will be particularly important to the economics of high sulfur spray drying applications because reagent-related costs are a major component of annual operating costs for these systems.

Alternate reagents that have been or are being tested in spray drying R&D programs include limestone, MgO, adipic acid-enhanced lime and limestone, thiosorbic lime, and lime or limestone with $CaCl_2$ addition. As discussed earlier in this section, recent EPA/EPRI-funded tests at the Riverside Station showed a 20 to 25 percent reduction in lime requirements for a 3.4 percent sulfur coal with addition of calcium chloride (see Section 3.8). Joy/Niro has also recently demonstrated a lime-based spray dryer process that removes both NO_x/SO_x with the addition of NaOH (see Section 3.10).

Renewed interest in the particulate removal performance of electrostatic precipatators (ESP) downstream of spray dryers has resulted from the potential applicability of spray drying as a retrofit technology for acid rain control. Information needs in this area include data on the resistivity of spray drying product for the various types coals and documentation of how FGD process conditions, such as approach to saturation and recycle ratio, may affect this resistivity.

In the waste disposal area, efforts are being directed primarily toward complete characterization of waste properties as a function of coal type and FGD process conditions.

2.3 DRY INJECTION

2.3.1 Commercial Activities

Dry alkali injection technology has not yet been commercially applied to either industrial or utility boilers. However, the first planned commercial application of dry injection technology has been announced by Public Service Company of Colorado for a 500 MWe unit scheduled for start-up in 1990. The system, which will use trona ore as the sorbent, will be designed for 70 percent SO_2 removal on a 0.4 percent sulfur western coal. The trona will be injected just upstream of the fabric filter into flue gas at approximately 132° to 138°C (270° to 280°F). A clay- and plastic-lined landfill will be used for solids disposal.

The application of trona dry injection had been previously constrained by questions regarding SO_2 removal limitations and cost. However, a recent EPRI-funded demonstration-scale study has shown that SO_2 removal efficiencies of 70 to 80 percent can be achieved with trona on low sulfur coals at reasonable stoichiometric ratios. Trona ore is currently mined in large quantities for conversion to sodium carbonate.

The commercial application of nahcolite dry injection still hinges on the economic availability of nahcolite. Nahcolite is not currently mined in the United States, but at least one firm has announced intentions to develop a nahcolite mining operation. Several other companies are investigating the possibility of supplying nahcolite through solution mining techniques.

A recent study has shown that dry injection economics are extremely sensitive to reagent costs. A key consideration for future dry injection applications will, therefore, be location of the plant relative to trona or nahcolite sources. Another important consideration for dry injection applications is the high solubility and leachability of the sodium-based wastes. Application of dry injection may be limited in some locations by the costs of disposing of the wastes in an environmentally safe manner.

2.3.2 Research and Development Activities

A full-scale demonstration of the dry injection process was completed in 1982 under EPRI-funding. The tests were conducted on a 22 MWe unit at the Public Service of Colorado's Cameo Station. Final reports on both nahcolite and trona dry injection have been prepared (3,4). The most recent results from the testing relate to the effects of sorbent type and the temperature at the point of injection on SO_2 removal. In general, the results showed that SO_2 removals of 70 percent can be achieved with nahcolite and trona at reagent ratios of 0.8 and 1.3, respectively. SO_2 removal by nahcolite was found to decrease dramatically below injection temperatures of 275°F, while SO_2 removal by trona appeared to be independent of injection temperature between 240° and 290°F. Details of the results are discussed in Section 3.7.

2.4 ELECTRON IRRADIATION SYSTEMS

The electron-beam process for SO_x/NO_x control is in an early developmental state. Pilot studies on both lime- and ammonia-based E-beam process configurations are currently underway or planned. These programs are being partially funded by the DOE and TVA. Research-Cottrell is developing the E-beam/lime spray dryer process, while EBARA International is developing the E-beam/ammonia injection process. The pilot systems will treat flue gas from high sulfur coal-fired boilers (see Section 3.5).

2.5 REFERENCES

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3. Muzio, L. J., et al. (KVB, Inc.) Dry SO_2 - Particulate Removal for Coal-fired Boilers. Volume 1: Demonstration of SO_2 Removal on a 22-MW Coal-fired Utility Boiler by Dry Injection of Nahcolite. EPRI CS-2894. Electric Power Research Institute, Palo Alto, California. March 1983.

4. Muzio, L. J., et al. (KVB, Inc.) Dry SO_2 - Particulate Removal for Coal Fired Boilers. Volume 2: Demonstration of SO_2 Removal on a 22-MW Coal-fired Utility Boiler by Dry Injection of Nahcolite, Trona and Soda Ash. EPRI Research Project 1682-2. In Press.

SECTION 3

CURRENT AND RECENTLY COMPLETED ACTIVITIES

This section reports the pertinent activities of private companies and government or other agencies involved in the development of dry FGD systems. Included here are descriptions of current and recently completed research and development activities and information on commercial systems sold or being marketed. Technical results from full-scale dry FGD operation and recent research and development programs are also discussed in this section.

3.1 BABCOCK AND WILCOX

Address: Babcock and Wilcox
20 South Van Buren
Barberton, Ohio 44023

Babcock and Wilcox
Alliance Laboratory
P. O. Box 834
Alliance, Ohio 44601

Contact for More Information:

Tom Hurst
Fossil Power Generation Division
Barberton, Ohio
(216) 753-4511

John Doyle
Alliance Laboratories
(216) 821-9110

Background

Babcock & Wilcox (B&W) has sold two utility spray drying systems: one to Basin Electric for the utility's Laramie River Station Unit 3 and one for Colorado Ute Power Company's Craig Station Unit 3. The B&W spray dryer system is based on the use of a horizontal flow reactor equipped with "Y-jet^{R}" spray nozzles adapted from B&W's standard oil burner technology. The Laramie River system will include an ESP, rather than a fabric filter, for particulate collection. B&W favors ESP's over fabric filters for their spray drying systems. However, depending on purchaser requirements or site-specific conditions, they will substitute a fabric filter for the precipitator. In fact, the Craig Station system will have a fabric filter at Colorado Ute's request.

B&W completed a relatively large-scale (120,000 acfm spray dryer) demonstration in the fall of 1980 at Pacific Power and Light's Jim Bridger Station. Recent R&D efforts are being directed toward pilot-scale studies with high sulfur coals.

Research and Development

Babcock and Wilcox (B&W) has recently completed a DOE-funded program to assess the applicability of dry scrubbing to high sulfur coal-fired boilers. Testing was conducted on a 1,500-acfm spray dryer/fabric filter system located at B&W's Alliance Research Center in Ohio. A final report on the testing is currently being prepared, with completion scheduled for mid- to late-1984.

Results from the pilot test program were presented at the 1983 EPA/EPRI FGD symposium in November and some of the results are summarized in this section. During the tests, a 2.6 to 3.0 percent sulfur bituminous coal was burned in a 5×10^6 Btu/hr combustion chamber, resulting in flue gas with SO_2 concentrations ranging from 1,900 to 2,300 ppm. Parameters varied during the testing included reagent type, operating mode (once-through or recycle), approach temperature, and spray dryer inlet temperature.

Once-through SO_2 removals for three different reagents are shown in Figure 3-1 as a function of reagent ratio. The reagents tested included soda ash, high calcium lime (93 - 97 percent CaO), and thiosorbic lime (88 percent CaO and 5 percent MgO). As expected, the highest SO_2 removals were obtained for soda ash. The thiosorbic lime showed lower SO_2 removals, at similar reagent ratios, than the high calcium lime. The lower SO_2 removals for the thiosorbic lime are probably due to the MgO present in the thiosorbic lime. Earlier pilot tests conducted for EPRI showed MgO to be somewhat less reactive with SO_2 than lime in the spray dryer. However, according to the lime vendor, another factor that may have contributed to the lower reactivity of the thiosorbic lime is poor calcination.

Results of tests conducted by B&W with once-through lime operation at various approach temperatures are shown in Figure 3-2. During these tests, gas exiting the spray dryer was reheated to at least 20°F above saturation before entering the fabric filter. The results show increased SO_2 removal with closer approaches to saturation temperature. SO_2 removals of 90 percent were achieved at a 1.2 reagent ratio and an approach to saturation of 15°F.

B&W also found that overall SO_2 removal for high sulfur coal increases with higher spray dryer inlet temperatures at a fixed reagent ratio and once-through lime operation. This effect is illustrated in Figure 3-3 for a reagent ratio of 1.0 and an approach to saturation of 35°F. At the higher inlet temperatures, more water must be evaporated into the flue gas to achieve the desired approach temperature. Thus, the solids content of the lime slurry fed to the atomizer is lower at higher temperatures. The

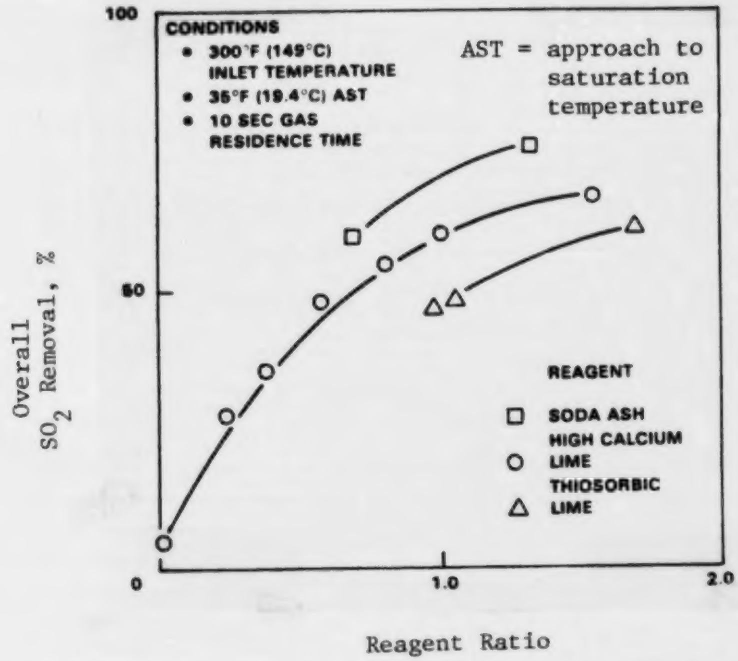

Figure 3-1. SO_2 removal vs. reagent ratio for different sorbents B&W pilot tests.

B&W

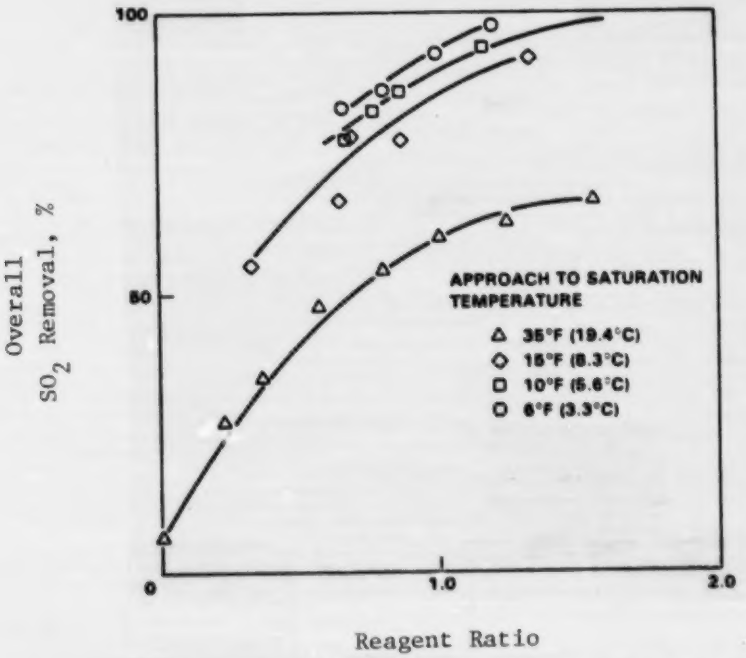

Figure 3-2. SO_2 removal variation with approach to saturation temperature during B&W pilot testing with lime reagent.

Source: Jankura, B. J., et al. See Information Sources at the end of this section.

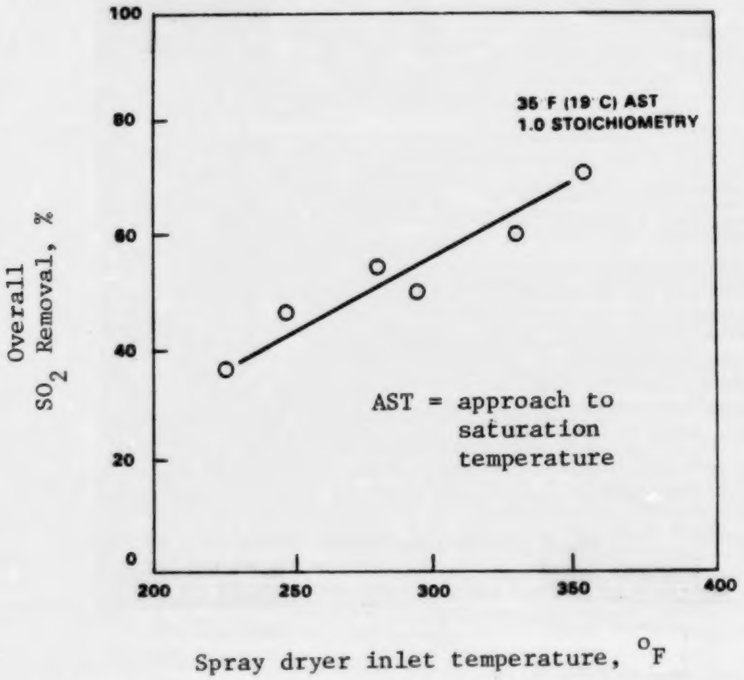

Figure 3-3. Effect of gas inlet temperature on SO_2 removal during B&W pilot testing with lime reagent.

Source: Jankura, B. J., et al. See Information Sources at the end of this section.

improved SO_2 removal at higher spray dryer inlet temperatures is believed to result from a longer critical drying time associated with this lower lime slurry solids content.

In tests conducted with solids recycle B&W found, as have other investigators, that lime utilization and SO_2 removal are significantly improved with recycle compared with once-through operation. B&W also concluded that solids recycle will be essential for dry scrubbing FGD on high sulfur coals. SO_2 removals of 90 percent were obtained with recycle at a reagent ratio of 1.6 and an approach to saturation of 20°F.

Commercial Activities

B&W's 575 MWe spray drying system at Basin Electric's Laramie River Station is currently operational, but has not yet met performance requirements. B&W is continuing development work to improve system performance. Current problems with the system relate to low spray dryer reactor capacity. One of the reactors has been recently modified to include four additional Y-jet nozzles (to total 16) to improve gas/liquid contacting. SO_2 removal for the modified reactor is approximately 75 percent at a reagent ratio of 1.5 without solids recycle and an approach to saturation of 30°F. Additional performance testing is planned through May 1984.

B&W's 450 MWe unit at Colorado Ute's Craig Station is currently scheduled for startup in mid-1984. This system is the same design as at Laramie River, but has a slightly longer residence time in the spray dryer reactor.

Information Sources

Larson, Brian, Basin Electric Power Company. Telephone conversation with M. A. Palazzolo, Radian Corporation, October 11, 1983.

Jankura, B. J., et al. "Dry Scrubber, Flue Gas Desulfurization on High Sulfur, Coal-Fired Steam Generators: Pilot Scale Evaluation." (Presented at the 1983 EPA/EPRI FGD Symposium, New Orleans, Louisiana, November 1-4, 1983.)

Jankura, B. J., Babcock and Wilcox. Telephone conversation with M. A. Palazzolo, Radian Corporation, December 20, 1983.

Hurst, T., Babcock and Wilcox. Telephone conversation with M. A. Palazzolo, Radian Corporation, February 27, 1984.

3.2 COMBUSTION ENGINEERING, INC.

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Environmental Systems Division
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Background

Combustion Engineering (C-E) began a dry scrubbing pilot plant research and development program in February 1979 at Northern States Power Company's Sherburne County Generating Station in Becker, Minnesota. Also, studies with a "second generation" pilot plant were conducted between 1979 and 1981 at Alabama Power Company's Gadsden Steam Plant.

Research and Development Activities

C-E is conducting research to improve rotary atomizer design to minimize maintenance requirements. No information on other research activities is available.

Commercial Activities

In August 1983, C-E obtained a letter of intent for a spray dryer/fabric filter system that is to be installed on a 40 to 50 MWe equivalent municipal waste incinerator. This incinerator is part of the San Francisco Bay Area Regional Resource Recovery Project. Current plans call for a single lime-based spray dryer with a rotary atomizer. The spray dryer will control SO_2, HF, and HCl emissions. No information on the concentrations of each pollutant is currently available. In addition to installing the dry scrubbing system, C-E is installing the boiler and is serving as the architect/engineering firm for the project.

Information Sources

Bresowar, Gerald. Combustion Engineering, Inc. Telephone conversation with M. A. Baviello, Radian Corporation, October 21, 1983.

Bresowar, Gerald. Combustion Engineering, Inc. Telephone conversation with M. A. Palazzolo, Radian Corporation, December 8, 1983.

3.3 COTTRELL ENVIRONMENTAL SCIENCES, INC.

Address: Cottrell Environmental Sciences, Inc.
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Cottrell Environmental Sciences
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Background

Cottrell Environmental Sciences (Cottrell) has completed demonstration-scale testing at two sites: privately-funded testing at Texas Utilities Big Brown Station and EPA-funded testing at Public Service of Colorado's Comanche Station. Demonstration-scale testing is currently being conducted by Cottrell at TVA's Shawnee Station.

Cottrell, in a joint venture with Komline-Sanderson, sold one commercial spray drying system to the United Power Association (Stanton Station) in January 1979. Komline-Sanderson supplies the spray dryer equipment and technology for the joint venture systems.

Research and Development Activities

Cottrell's 10,000 acfm spray dryer/fabric filter system, formerly located at Public Service of Colorado's Comanche Station, has been moved to TVA's Shawnee Station (Unit #10) to study high sulfur coal applications. Some preliminary results using 3.5 percent sulfur coal indicate an SO_2 removal rate greater than 90 percent with inlet SO_2 concentrations ranging from 2,800 to 3,000 ppm. This was achievable at a reagent (lime) ratio of 1.5 or less.

In October 1983, a study was begun at Shawnee to assess the performance of an ESP downstream of a spray dryer with the use of high sulfur coal. Tests will soon be conducted on alternate reagents and additives to increase lime utilization. The results of these studies will be available in early 1984.

Shawnee is also the site for an electron-beam irradiation project that is jointly funded by DOE, TVA, and Research-Cottrell (see Section 3.5).

Commercial Activities

Cottrell's 60 MWe spray dryer system at United Power Association's Stanton Station began operating in September 1982. This lime-based system consists of one spray dryer, three rotary atomizers, a reverse-air fabric filter, and a reagent preparation system. United Power Association is currently investigating the economic impact of adding flyash recycle to the reagent preparation system.

Performance tests conducted in July 1983 indicated that the Stanton system met design specifications. Using 0.77 percent and 1.94 percent sulfur lignites, this system is designed to have an SO_2 removal efficiency of 73 percent and 91 percent, respectively. Preliminary results from compliance tests conducted in October 1983 showed outlet SO_2 emissions of 0.45 $lb/10^6$ Btu and an SO_2 removal efficiency of 69.6 percent on a 0.7 percent sulfur coal. No reagent ratios were reported for these tests. The Stanton system has not yet been turned over to the United Power Association for commercial operation.

Information Sources

Widico, Mike. Cottrell Environmental Sciences. Telephone conversation with M. A. Baviello, Radian Corporation. October 18, 1983.

Roop, Robert. Cottrell Environmental Sciences. Telephone conversation with M. A. Baviello, Radian Corporation. October 17, 1983.

3.4 DOE/CONSOL/CONOCO AND DOE/EPA

Address: U. S. Department of Energy
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Background

The Niro/Joy designed spray drying FGD system at the Argonne National Laboratory has been operating since December 1981 and was turned over to Argonne for operation in late 1982. During 1983, three types of process tests were conducted on the Argonne system: Niro/Joy conducted industrial-scale testing of their new SO_x/NO_x process, DOE/Consolidation Coal/Conoco Coal Research conducted demonstration testing on a 4.2 percent sulfur coal, and the EPA's Emission Standards and Engineering Division (ESED) conducted performance tests for use in the development of new source performance standards (NSPS) for industrial boilers. Results of the NO_x/SO_x testing are discussed with Joy/Niro's activities in Section 3.11, and major results from the other two test programs are summarized in this section. Results of waste disposal characterization studies conducted by Argonne are discussed in Section 5.

Demonstration

In April 1983, Argonne National Laboratory, Consolidation Coal Company (Consol) and Conoco Coal Research Division conducted a series of tests to demonstrate the applicability of spray drying technology to high sulfur coal-fired boilers. The Argonne spray drying system is a typical Joy/Niro design with a single spray dryer, equipped with a rotary atomizer, followed by a pulse-jet fabric filter. The system uses a paste slaker and solids recycle to provide an atomizer feed slurry with a solids content of approximately 35 percent by weight. During the testing, the Argonne stoker boiler fired a West Virginia bituminous coal with a sulfur content of 4.2 percent, an ash content of 8.9 percent, and a heating value of 12,700 Btu/lb. The boiler operated between 50 and 75 percent of its rated capacity of 170,000 lb steam/hr. Flue gas SO_2 concentrations at the spray dryer inlet, spray dryer outlet, and fabric filter outlet were determined using EPA Method 6.

Major results from the recent Argonne high sulfur tests are in the areas of lime reagent utilization, approach temperature effects, spray dryer product resistivity, and SO_2 removal. Figure 3-4 shows overall SO_2 removal

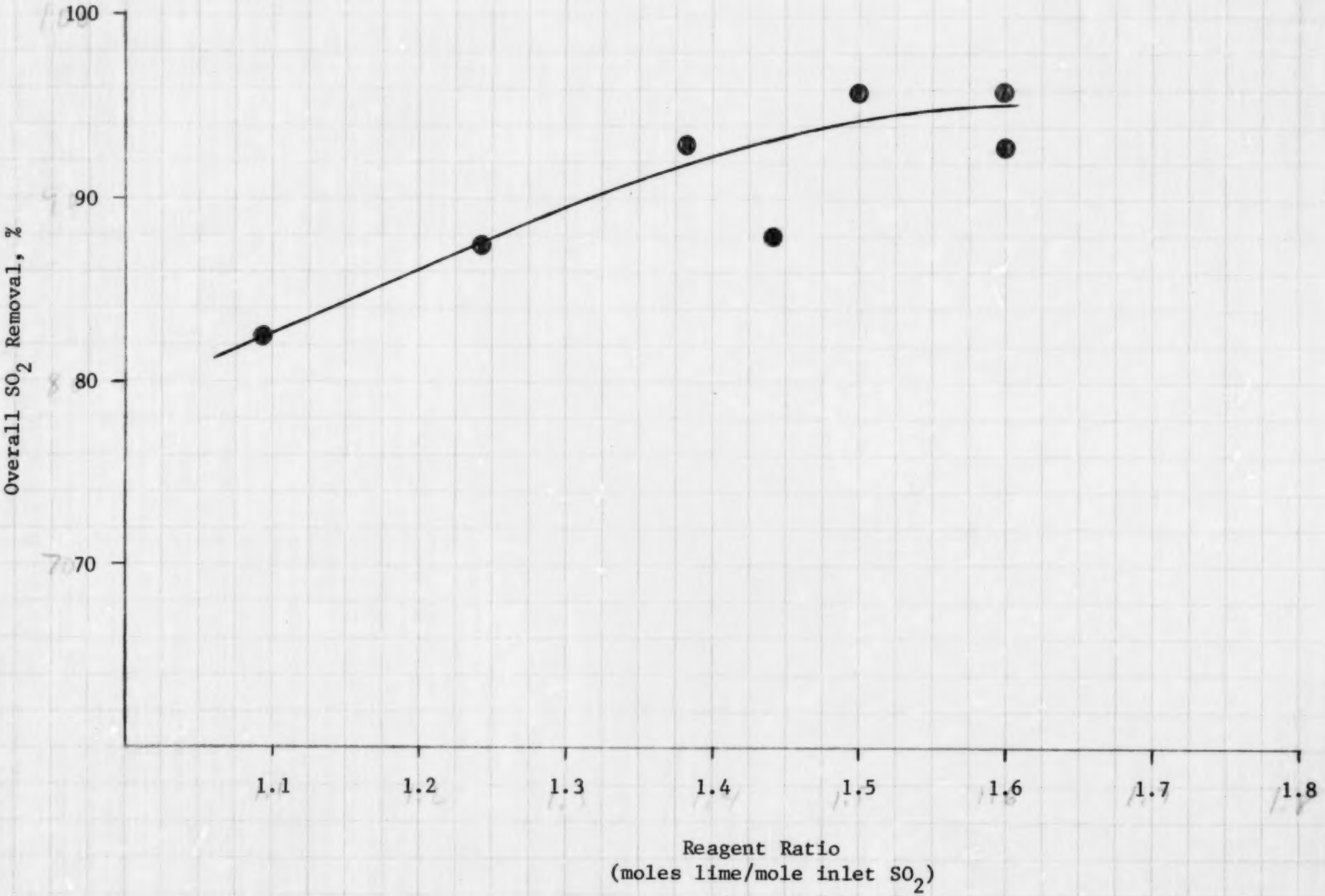

Figure 3-4. SO_2 removal vs. reagent ratio for Argonne tests at 20°F approach temperature.

Source: Farber, P. S., et al. See Information Sources at the end of this section.

as a function of reagent ratio at an approach to saturation of 20°F. The data show that the Argonne system achieved 90 percent SO_2 removal with solids recycle at a reagent ratio of approximately 1.3. This reagent ratio is comparable to that required for 90 percent SO_2 removal with a 3.4 percent sulfur coal at the NSP Riverside Station (see Section 3.8). Results of tests conducted at Argonne to assess the effect of approach to saturation temperature are shown in Table 3-1. Reductions in the approach temperature from 30° to 20°F resulted in overall SO_2 removal increases ranging from 19 to 12 percent at reagent ratios of 1.1 to 1.3.

The resistivity of the gas-entrained solids from the spray dryer was also determined during the Argonne testing. Results of in-situ and laboratory (bulk) resistivities measurements are shown in Figure 3-5. The resisitivities were found to be typical of fly ash resistivity for many medium and high sulfur eastern coals. In addition, the in-situ measurements showed an extremely strong dependence of resistivity on outlet temperature near an approach to saturation of 20°F (nominal 145°F spray dryer outlet). It should be noted that the resistivity of the gas-entrained solids (fly ash-lime-reaction products) at Argonne may not typify that of solids from a pulverized coal-fired boiler. Fly ash loadings in flue gas from pulverized coal-fired boilers are generally much higher than for stoker-fired boilers. In addition, the Argonne boiler uses a cyclone to collect a large percentage of fly ash prior to the flue gas entering the spray dryer.

In the area of fabric filter SO_2 removal, Argonne/Consol/Conoco found that the contribution of the fabric filter to overall SO_2 removal was between 20 and 30 percent, based on the spray dryer inlet SO_2 concentration. In addition, they reported that the percent SO_2 removal across the spray dryer and across the fabric filter were approximately equal, based on the inlet SO_2 concentration to each device.

Results of an economic evaluation conducted by Conoco based on the Argonne results shows that lime spray drying FGD is competitive with limestone wet scrubbing for high sulfur applications. The basis for the evaluation was a 500 MWe utility system achieving 90 percent SO_2 removal on a 3.2 percent sulfur coal. A similar evaluation for a hypothetical retrofit application requiring 70 percent SO_2 removal showed a significant economic advantage for a spray dryer/existing ESP system compared to a wet limestone scrubber, provided that no ESP modifications are required. A more detailed discussion of this cost analysis is given in Section 4.

Performance tests were also conducted at Argonne under EPA funding. During these tests, the stoker boiler fired its normal 3.2 percent sulfur Illinois coal. Results of tests conducted under normal system operation showed daily SO_2 removals ranging from 82 to 92 percent with corresponding outlet SO_2 emission levels of 0.87 to 0.38 $lb/10^6$ Btu, respectively. The reagent ratio required for an average 86.8 percent removal was approximately 1.1 at an approach to saturation of 27°F. SO_2 concentrations were determined by a 24-hour wet sampling method (EPA Method 6B).

TABLE 3-1. EFFECT OF APPROACH TEMPERATURE DURING ARGONNE HIGH SULFUR TESTS

Approach to Saturation °F	Ca/S Mol Ratio	Sulfur Removal, %
30	1.1	64
20	1.1	83
30	1.2	78
20	1.2	84
30	1.3	74
20	1.3	87

Source: Farber, P. S., et al. See Information Sources at the end of this section.

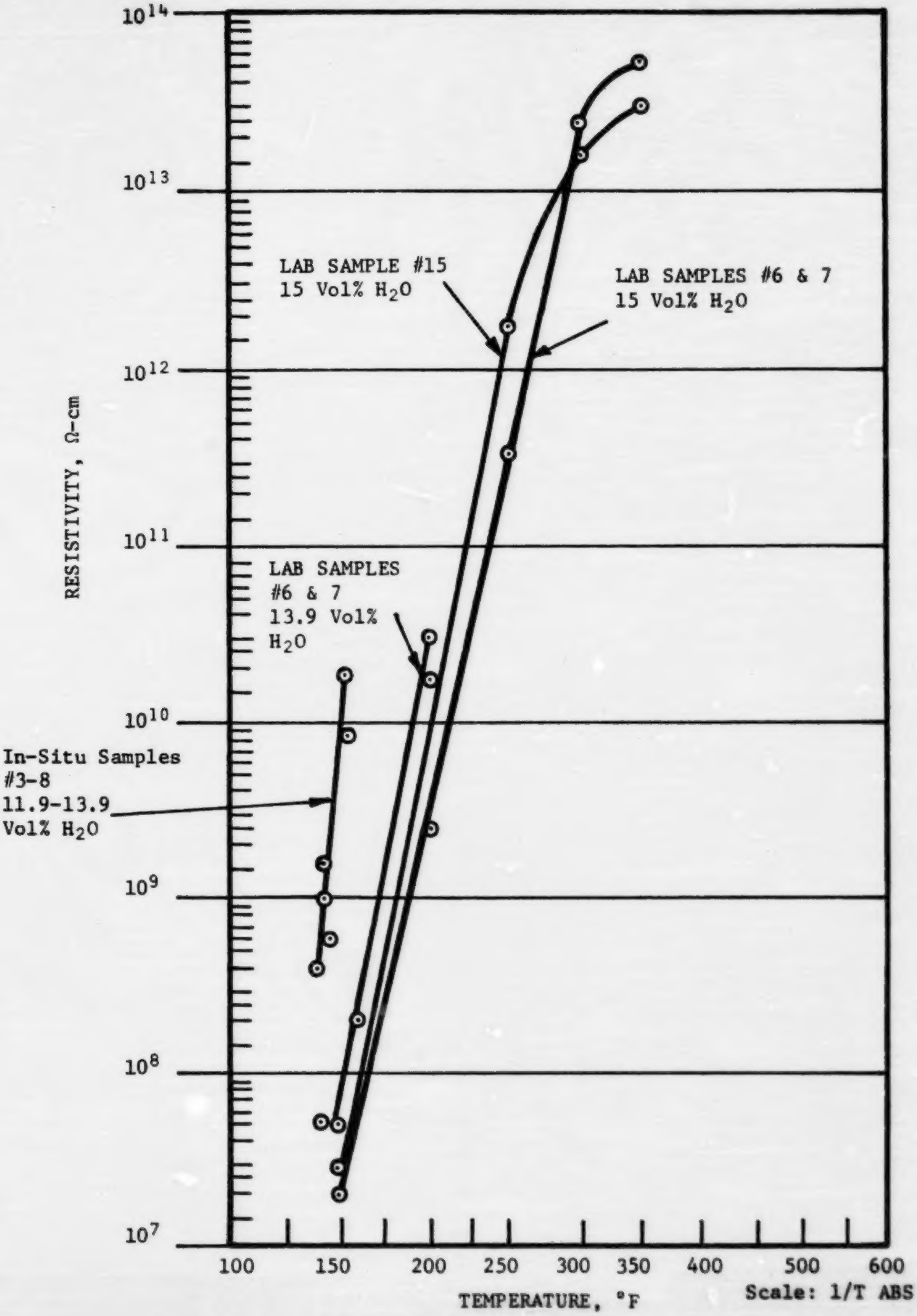

Figure 3-5. Electrical resistivity of Argonne spray-dried product.

Source: Farber, P. S., et al. See Information Sources at the end of this section.

Information Sources

Farber, P. S., et al. "Evaluation of a Spray Dryer Flue Gas Cleaning System on High Sulfur Coal." (Presented at the 1983 Coal Technology Conference, Houston, Texas, November 15-17, 1983.)

Rohlack, L. A., et al. Industrial Boiler Continuous Emission Monitoring at Argonne National Laboratory. (Draft Final Report prepared for U. S. Environmental Protection Agency, Research Triangle Park, North Carolina, EPA Contract No. 68-02-3542.)

3.5 DOE/EBARA/AVCO-EVERETT AND DOE/RESEARCH-COTTRELL

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Pittsburgh, Pennsylvania 15236

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Background

EBARA Corporation of Japan conducted initial work on an ammonia-based electron irradiation process in the early 1970's and tested a 3-MWe pilot unit at a steel sintering plant in 1977 and 1978. EBARA later joined with Avco-Everett, a U. S. Company that has been conducting bench-scale studies since 1977. DOE's involvement in E-beam NO_x/SO_x control began in 1979 when Research-Cottrell performed bench-scale studies on a lime-based E-beam process under a DOE contract.

Research and Development

Research-Cottrell is currently evaluating the E-beam/lime process with a 10,000 to 15,000 acfm pilot plant installed at TVA's Shawnee Station. Using flue gas from firing a 2.5 to 3 percent sulfur coal, NO_x and SO_2 removal optimization tests will be conducted at electron irradiation rates between 0.5 and 1.5 Mrad (1 Mrad is equivalent to 10 joules/g of flue gas). Research-Cottrell may also conduct nitrate fixation tests and electron-gun cost reduction studies. This 6-month research program is cooperatively funded by DOE, TVA, and Research-Cottrell. Testing began in February 1984.

EBARA will evaluate the E-beam/ammonia injection process. A 20,000 acfm pilot plant, capable of treating flue gas from firing a 2.5 to 3 percent sulfur coal, is under construction at Indianapolis Power and

Light's E. W. Stout plant. Following optimization and reliability testing, EBARA plans to investigate the potential use of waste products from the process as fertilizer. This 12-month project is cooperatively funded by DOE, EBARA, the State of Indiana, several Indiana-based utilities, a coal company, and a fertilizer company.

Under a previous DOE contract, AVCO Corporation had the lead role in the E-beam research while EBARA had the support role. AVCO is conducting an E-beam kinetic study at their AVCO-Everett Research Laboratory. This study was scheduled for completion in December 1983.

Information Sources

Williams, John E., DOE-Pittsburgh, PA. Status of the DOE Gas Cleanup Program. Presented at the 8th Symposium on Flue Gas Desulfurization, New Orleans, Louisiana, November 1-4, 1983.

Williams, John E., DOE-Pittsburgh, PA. Telephone conversation with M. A. Palazzolo, Radian Corporation, August 2, 1983.

Feldman, Paul, Research-Cottrell. Telephone conversation with M. A. Palazzolo, Radian Corporation, March 1, 1984.

3.6 ECOLAIRE ENVIRONMENTAL COMPANY

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Background

Ecolaire has sold a total of five industrial spray drying units: one unit to Container Corporation (Philadelphia, PA) and four units for Griffiss Air Force Base (Rome, NY). In addition, the company has constructed and tested a mobile spray dryer/fabric filter system.

Commercial Activities

In mid-1983, Ecolaire sold four industrial spray drying units to Griffiss Air Force Base for boilers burning 3 percent sulfur coal. Each of the four 90,000 lb steam/hr boilers will be equipped with a spray dryer and a pulse-jet fabric filter. The spray drying units are designed to achieve

85 percent SO_2 removal and will each treat 50,000 acfm of flue gas at 350°F. A single lime preparation area will provide reagent slurry (fresh lime plus recycle) for all four units. Outlet SO_2 and particulate emission level guarantees are for 0.71 and 0.05 lb/10^6 Btu, respectively. Start-up of the units is scheduled for the Fall of 1984.

The spray dryer/fabric filter system at Container Corporation has been operational since March 1982. The system was turned over to Container following compliance and performance tests conducted in April and July 1982. Results of three EPA Method 6 test runs showed an average outlet SO_2 emission rate of 0.03 lb/10^6 Btu and an average outlet particulate emission rate of 0.008 lb/10^6 Btu. The SO_2 emission rate corresponds to an SO_2 removal efficiency of approximately 97 percent for the 0.6 percent sulfur coal. No data on the reagent ratio or approach to saturation temperature have been reported for these tests.

Information Sources

Horn, Richard, Ecolaire Environmental Company. Telephone conversation with M. A. Palazzolo, Radian Corporation. October 11, 1983.

Mueller, M. D. (Betz-Converse-Murdoch, Inc.). Emissions Evaluation of the Number 1 Boiler Stack for Container Corporation of America, Philadelphia, Pennsylvania, (BCM Project No. 00-4297-18), November 1982.

3.7 EPRI

Address: Electric Power Research Institute
3412 Hillview Avenue
P. O. Box 10412
Palo Alto, California 94303

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Spray Drying/Waste Characterization Activities:

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EPRI Project Manager
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Dry Injection Activities:

Richard Hooper
EPRI Project Manager
Arapahoe Office (Denver, Colorado)
(303) 936-7281

Background

The Electric Power Research Institute's (EPRI's) Air Quality Program is currently conducting or has recently completed dry FGD programs involving pilot- and demonstration-scale spray dryer testing and demonstration-scale dry injection testing. The demonstration-scale spray dryer tests, which were conducted at Northern States Power Company's Riverside Station and were jointly funded by EPA/EPRI, are discussed in Section 3.8. The status and major results of the other recent EPRI-funded dry FGD programs are discussed in this section.

Spray Drying Research and Development

EPRI, with Radian Corporation as the prime test contractor, is conducting tests with a nominal 8,000-acfm spray dryer/fabric filter system located at a research facility at the Public Service of Colorado's Arapahoe Station. The results of testing, which began in March 1982 and is currently scheduled to last through mid-1984, will be used to assess the operability of lime-based spray dryer FGD systems and provide design data for typical utility installations. An interim report on the results of testing from March 1982 through June 1983 is currently being prepared. The primary emphasis of the test program so far has been on low to moderate sulfur coal operation (up to 2 percent sulfur), with removal efficiencies of 70 to 90 percent. The majority of the tests have been conducted with solids recycle although some tests have been made in a once-through operating mode.

Figure 3-6 is a simplified process flow diagram for the pilot system. The 10-ft diameter spray dryer, which can accommodate either rotary or nozzle atomization, has a 5.5-ft straight side and a 50° cone bottom. The vessel has interchangeable vane rings, one for normal gas flow rates and one for low flows, and can be arranged for either bottom or side gas exit. The vessel also has a bolt-in side section which can be installed to double the volume of the dryer, thereby doubling the gas residence time. At normal flue gas rates and without the added side section, the dryer residence time is 5.0 to 5.5 seconds. The gas residence time for most commercial system designs is between 8 and 12 seconds. Most of the testing at Arapahoe has been conducted at a flue gas flowrate of approximately 6,500 acfm, corresponding to a 7-second residence time.

The fabric filter for the pilot system is one compartment of a 10 MWe equivalent four-compartment unit which EPRI had previously tested for over a year. At 6,500 acfm the air-to-cloth ratio is 1.7 ft/min. The fiberglass bags can be cleaned by either reverse-air or shake/deflate methods or a combination of the two techniques. Tests discussed in this section were conducted with reverse-air cleaning.

The reagent preparation area contains both a ball mill, a paste-type slaker, and a detention-type slaker (not shown in Figure 3-6). The feed slurry is fed to the atomizer with progressive cavity pumps. Just prior to

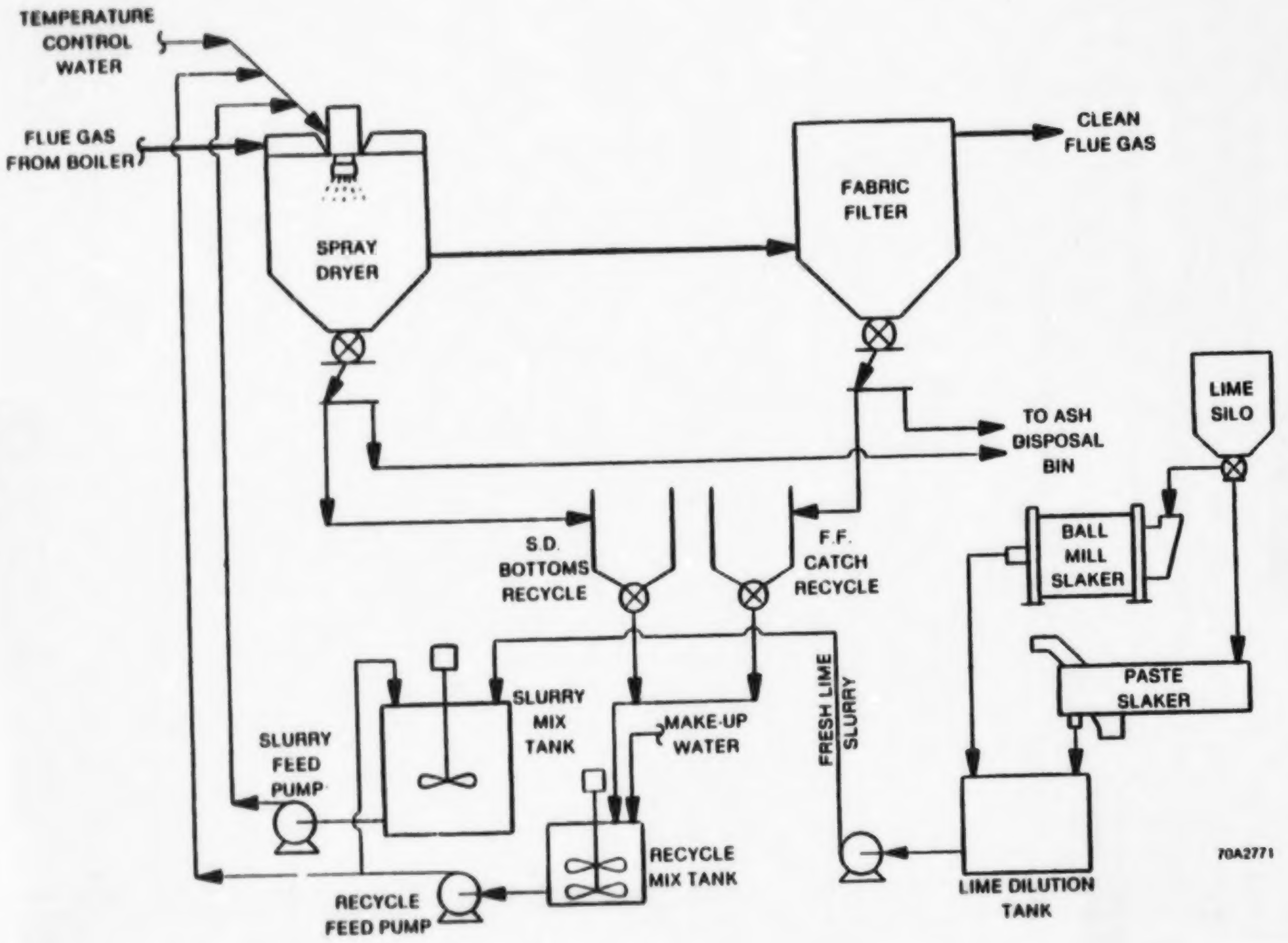

TEMPERATURE CONTROL WATER
FLUE GAS FROM BOILER
SPRAY DRYER
FABRIC FILTER
CLEAN FLUE GAS
TO ASH DISPOSAL BIN
LIME SILO
BALL MILL SLAKER
S.D. BOTTOMS RECYCLE
F.F. CATCH RECYCLE
SLURRY MIX TANK
MAKE-UP WATER
FRESH LIME SLURRY
PASTE SLAKER
SLURRY FEED PUMP
RECYCLE MIX TANK
RECYCLE FEED PUMP
LIME DILUTION TANK
70A2771

Figure 3-6. Simplified process flow diagram for Arapahoe spray dryer pilot plant (rotary atomizer configuration).

the atomizer, the feed slurry is combined with dilution water metered to control the dryer outlet temperature at the desired approach to saturation. Automatic slurry feed rate control is based on the outlet SO_2 concentration. Solids can be recycled from either the spray dryer bottom catch, the fabric filter catch, or both. The system also has the capability for testing three recycle configurations:

- recycle solids added directly to fresh feed tank,
- recycle solids slurried and then added to fresh feed tank, and
- separate recycle and feed slurries combined just upstream of the atomizer.

The recycle addition rate is based on ratio controls tied to the fresh lime feed rate. Recycle test results discussed in this section are for fabric filter solids added directly to the fresh lime feed tank.

Key results from the testing at Arapahoe relate to spray dryer operation, SO_2 removal efficiency, and fabric filter operation. Major parameters or operating conditions varied during these tests include the following:

- spray dryer operating mode (i.e., once-through or solids recycle),
- dryer residence time,
- inlet SO_2 concentration,
- recycle ratio (lb recycle/lb fresh slaked lime),
- spray dryer inlet temperature, and
- makeup water composition.

One important conclusion from the EPRI pilot testing is that spray dryer operability and SO_2 removal are both improved by operation in the recycle rather than the once-through mode. These improvements appear to be related to the increased solids content in the slurry fed to the atomizer as well as to the other benefits of recycling in improving reagent utilization. The effect of operating conditions at Arapahoe on the weight percent solids in the atomizer feed slurry and the condition of the spray dryer product is summarized in Table 3-2. As shown in the table, once-through operation at low inlet SO_2 concentration results in the lowest solids content in the slurry fed to the atomizer. At these operating conditions, buildup of wet solids on the spray dryer walls was observed. At other operating conditions, where the atomizer feed solids content was higher, no problems with wet solids were encountered and spray dryer operability was improved. These observations are supported by theoretical considerations for the drying of droplets in a spray dryer. This theory predicts that droplets with a high weight percent solids (e.g., 30 percent) will have a significantly shorter "critical drying time" than droplets with a lower solids content, such as 5 or 10 percent solids.

TABLE 3-2. EFFECT OF OPERATING CONDITIONS ON WEIGHT PERCENT SOLIDS AND SPRAY DRYER (S.D.) PRODUCT.

Operating Mode	Nominal Inlet SO_2 (ppm)	Weight Percent Solids to Atomizer Wheel	Vessel Residence Time (sec)	Nature of S.D. Product
Once-through	350	3 to 7	7	Wet
Recycle (2:1)	350	6 to 16	7	Dry
Recycle (6:1 to 8:1)	350	17 to 24	7	Dry
Recycle (12:1)	350	31 to 37	5	Dry
Once-through	1000	12 to 16	7	Dry
Recycle (2:1)	1000	20 to 34	7	Dry
Recycle (2.5:1)*	1000	25*	5	Dry

*One test.

SO_2 removal results for once-through and recycle operation are compared for different inlet SO_2 levels in Figures 3-7 and 3-8. Spray dryer, fabric filter, and overall SO_2 removals are all shown in these figures as a function of reagent ratio. Data in Figure 3-8 were collected at 400 ppm inlet SO_2, and data in Figure 3-7 are for 1,000 ppm. The dashed curves in Figure 3-8 are best fit curves for the 400 ppm recycle tests shown in Figure 3-9. Recycle tests were conducted with a recycle ratio of 2:1.

The data in Figures 3-7 and 3-8 confirm the results of other investigators, showing an improvement in SO_2 removal with recycle compared with once-through operation. The increase in SO_2 removal occurs in the spray dryer rather than in the fabric filter and is somewhat less pronounced for the 1,000 ppm tests compared to those at 400 ppm.

Results of tests conducted at higher recycle ratios at 400 ppm are shown in Figure 3-10. EPRI reported that recycle ratios of approximately 6:1 to 8:1 did not show a significant improvement in SO_2 removal over a 2:1 recycle ratio (Figure 3-9). However, reagent ratios of 12:1, corresponding

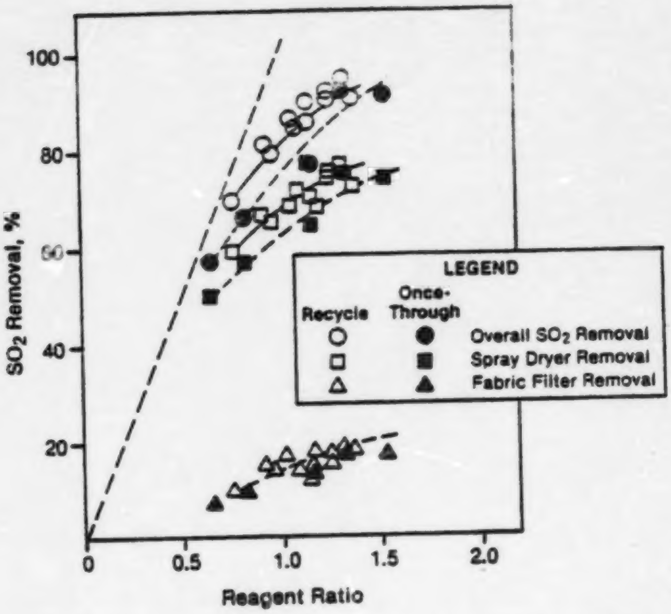


Figure 3-7. Comparison of recycle versus once-through operation results for 1,000 ppm inlet SO_2.

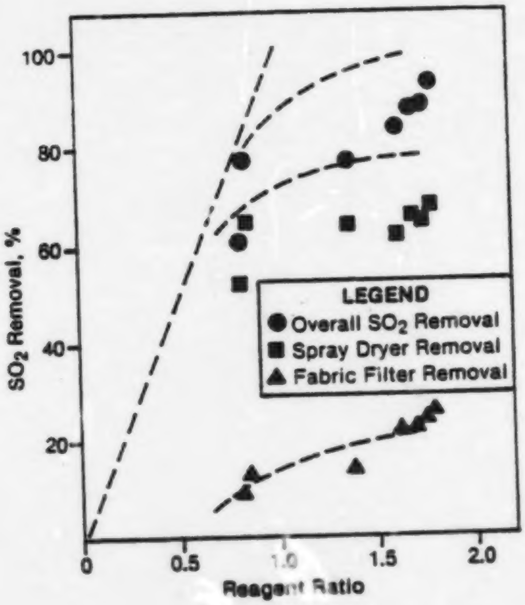


Figure 3-8. Comparison of once-through SO_2 removal points with best fit curves from recycle results for 400 ppm inlet SO_2 levels.

Source: Blythe, G. M., et al. See Information Sources at the end of this section.

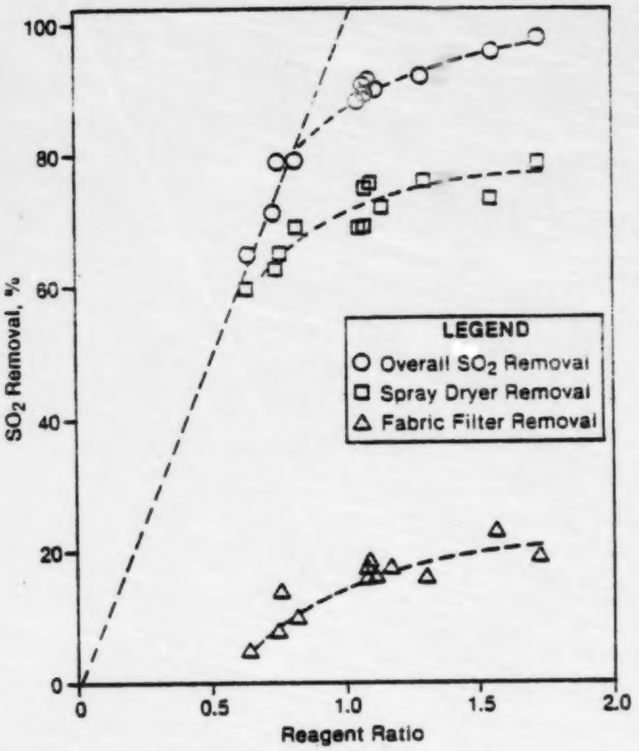


Figure 3-9. Baseline SO_2 removal for 400 ppm inlet SO_2, 20° approach, 2:1 recycle ratio.

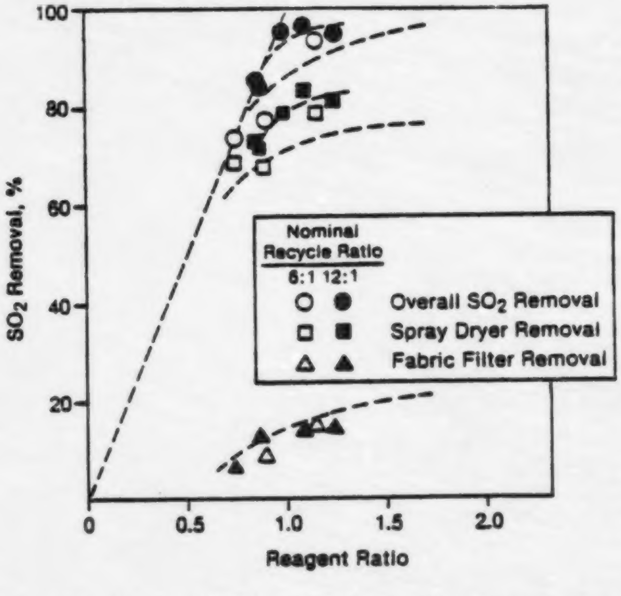


Figure 3-10. Results of high recycle ratio tests at 400 ppm inlet SO_2.

Source: Blythe, G. M., et al. See Information Sources at the end of this section.

to a weight percent solids of 30 percent or greater in the atomizer feed slurry, showed a marked improvement, primarily in SO_2 removal in the spray dryer.

No bag fabric problems were observed during the EPRI pilot testing despite numerous system start-ups and shut-downs and several severe spray dryer upset conditions. However, a problem did occur with corrosion on the baghouse walls. This problem was attributed to (1) the fact that all four walls of the baghouse compartment are exposed to ambient temperatures and (2) the baghouse was designed to clean hot flue gas (250° to 300°F) and has only a 2-inch thickness of insulation. EPRI feels that corrosion problems in a fabric filter downstream of a spray dryer can be avoided through the use of adequate insulation thicknesses and careful design and installation to avoid localized cold spots. This may require insulation between compartment walls to avoid cold walls when adjacent compartments are off-line.

Another important finding from the EPRI pilot testing is that a baghouse downstream of a spray dryer may operate at substantially lower pressure drop than a baghouse treating normal fly ash-laden flue gas, particularly if the bags are not conditioned by a lengthy period of fly ash only operation. Pressure drop data for new bags in two compartments of the Arapahoe pilot baghouse are shown in Figure 3-11. Those bags showing higher pressure drop are for a compartment collecting only fly ash. The bags showing a lower pressure drop were started up downstream of the spray dryer without fly ash pre-conditioning.

Tests were also conducted at Arapahoe to determine the suitability of two simulated cooling tower blowdown (CTB) streams as makeup (mixing and temperature control) water to spray drying systems. The compositions of the two streams are shown in Table 3-3. Results of tests with the simulated CTB streams showed improved or equivalent SO_2 removals in both cases. EPRI and Radian concluded from these tests that CTB streams appear to be an acceptable and sometimes beneficial source of makeup water for spray drying systems. It should be noted that this conclusion applies only to CTB used for mixing and temperature control. The impact of using CTB streams for lime slaking was not fully investigated during the EPRI pilot testing. Also, Buell Emission Control Division, during a pilot study conducted for EPA (see Parsons et al. at the end of this section), found that CTB adversely affected lime slaking, while little or no effect on SO_2 removal was observed when CTB was used as makeup water only.

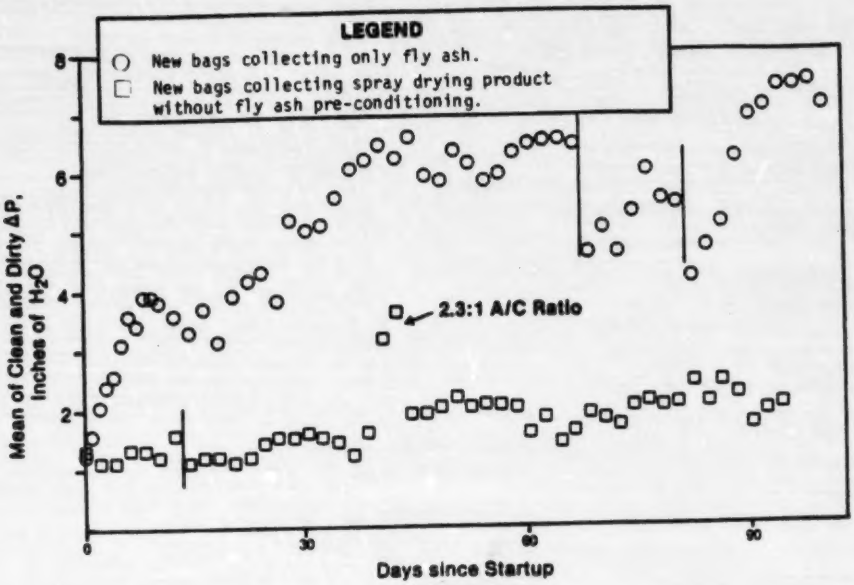


Figure 3-11. Comparison of previous start-up of a compartment on fly ash to a recent start-up of a compartment downstream of spray dryer.

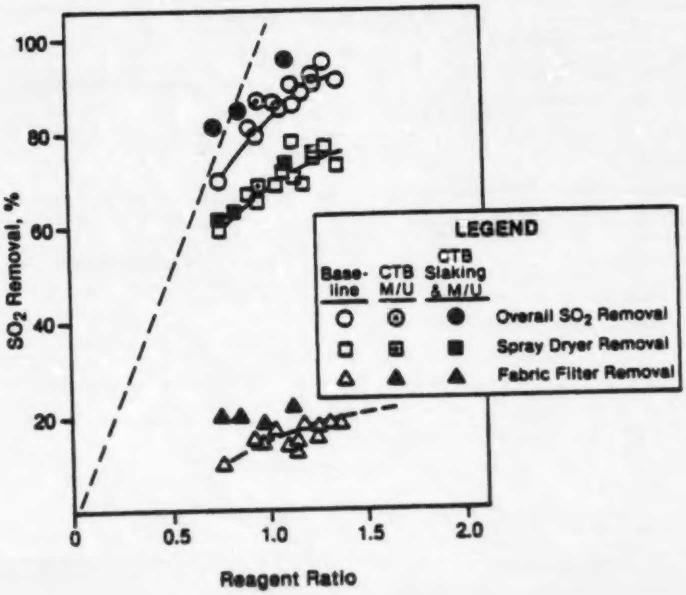


Figure 3-12. 1,000 ppm inlet SO_2 recycle results for baseline conditions when using simulated cooling tower blowdown No. 1 for slaking and makeup water.

Source: Blythe, G. M., et al. See Information Sources at the end of this section.

TABLE 3-3. NOMINAL COMPOSITIONS OF SIMULATED COOLING TOWER BLOWDOWN WATERS (mg/L)

Component	CTB No. 1	CTB No. 2[a]
Ca^{++}	1160	410
Na^{+}	480	1830
Mg^{++}	-	53
$SO_4^{=}$	1000	5080
Cl^{-}	2050	170

[a] Includes 10 ppm AMP, HEDP, or polyacrylate scale inhibitors for some runs.

The presence of high chloride levels (∿ 2,050 ppm) in CTB No. 1 resulted in a substantial enhancement of SO_2 removals as shown in Figure 3-12. This enhancement effect, which is most likely caused by the deliquescent properties of $CaCl_2$, is discussed further later in Section 3.8 with the results of testing conducted at NSP's Riverside Station.

A final conclusion from the EPRI pilot testing relates to the effect of low spray dryer inlet temperature at 400 ppm inlet SO_2. Operation at a reduced inlet temperature of 210° to 220°F compared to the "normal" inlet of 260° to 280°F did not have a substantial impact on SO_2 removal performance or lime utilization. Results of the low inlet temperature tests are shown in Figure 3-13. These tests were conducted at an approach to saturation of 20°F and corresponded to spray down temperatures of approximately 155° and 105°F for the normal and low inlet temperatures, respectively.

Testing of the Arapahoe spray drying pilot unit is currently scheduled to continue through mid-1984. Studies planned for this period include evaluation of the following:

- reactivity of various limes,
- effect of low slaking temperatures,
- reagent requirements at high inlet SO_2 (2,000 ppm),
- effect of chloride addition,

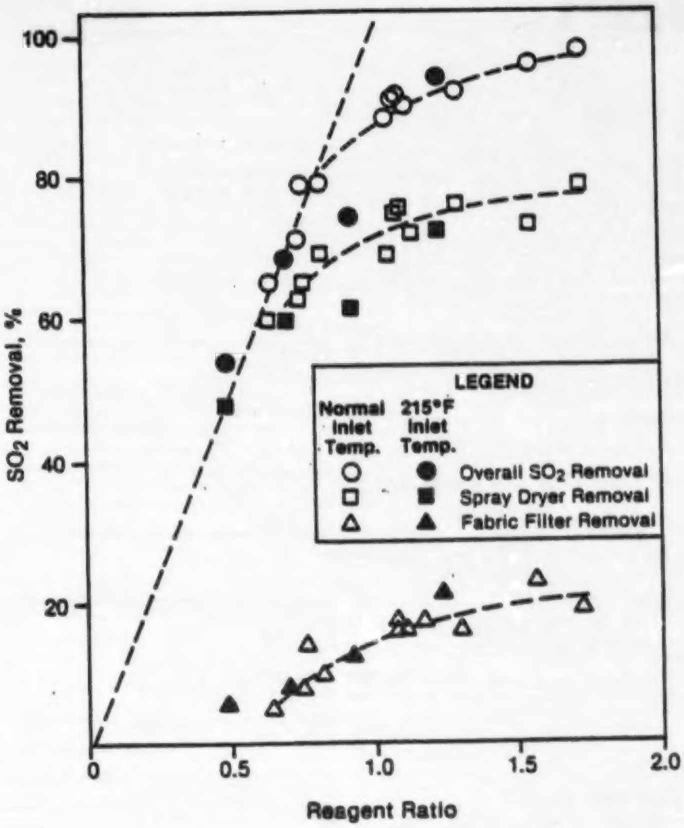


Figure 3-13. Effects of reduced inlet temperature on SO_2 removal for 400 ppm inlet SO_2, recycle operation.

Source: Blythe, G. M., et al. See Information Sources at the end of this section.

- SO_2 removal capability of fine ground limestone with and without chloride addition,
- reagent requirements at low SO_2 removals (50 percent),
- effect of bypass reheat, and
- effects of bag cleaning methods and cycles.

Dry Injection Demonstration

A full-scale demonstration of the dry injection process was completed in 1982 by KVB, Inc. under EPRI funding. The tests were conducted on a 22 MWe unit at the Public Service of Colorado Cameo Station. Final reports on both nahcolite and trona injection have been prepared. The most recent results from the testing, which relate to sorbent type and the effect of temperature at the point of injection, are discussed briefly in this section. Important results from earlier test work are also presented.

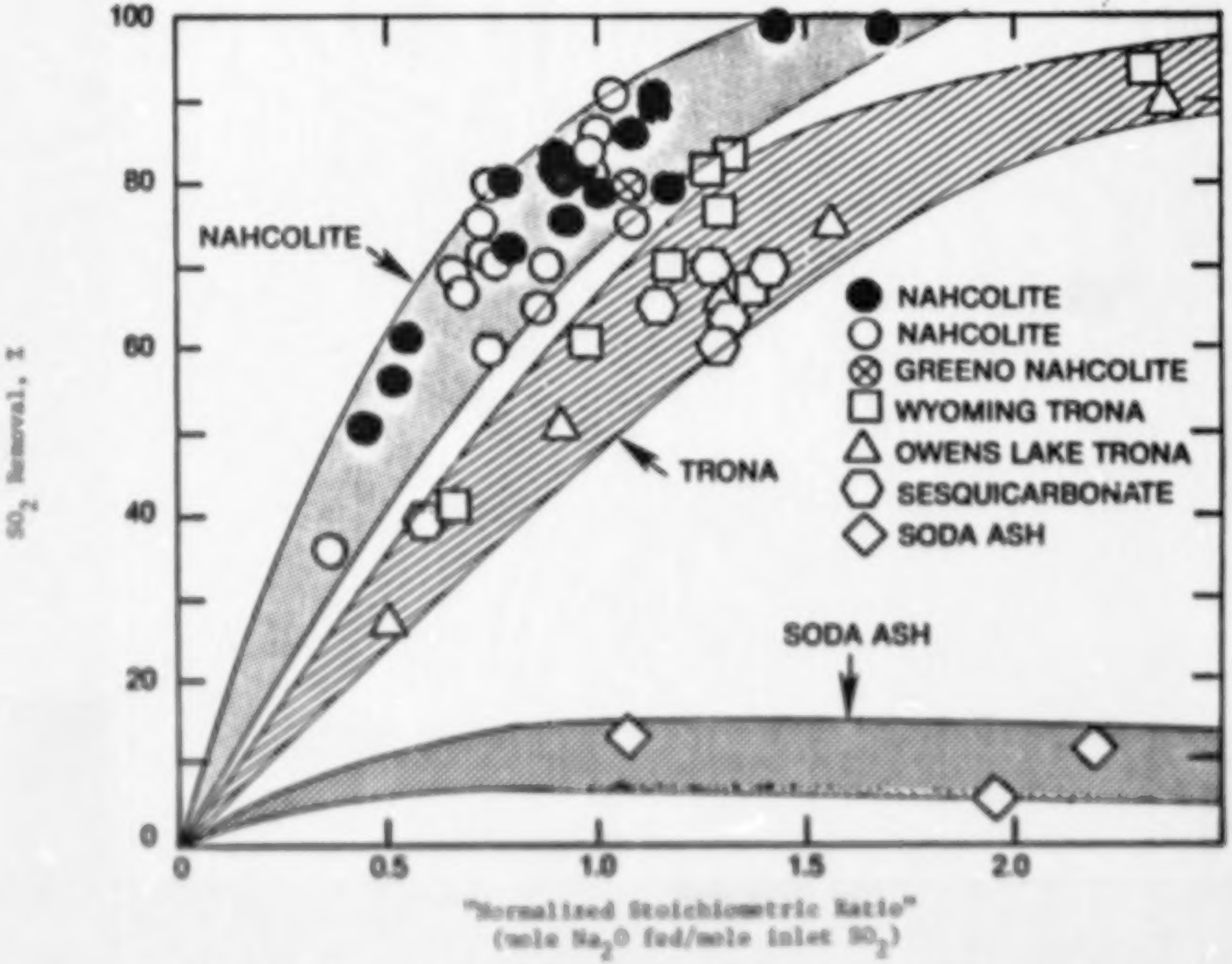
The system at Cameo consists of a 22 MWe coal-fired boiler with an eight-compartment reverse-air fabric filter. During the dry injection testing, the boiler fired a 0.4 percent sulfur western coal, resulting in flue gas with a nominal SO_2 concentration of 450 ppm. Sorbent was normally injected into 275° to 290°F flue gas approximately 50 feet upstream of the fabric filter.

Results of tests conducted at Cameo with nahcolite, trona, and soda ash are shown in Figure 3-14. Sulfur dioxide removals of 70 and 90 percent were achieved with nahcolite at stoichiometric ratios of approximately 0.8 and 1.1, respectively. For trona ore, this same system showed SO_2 removals of 70 and 90 percent at stoichiometric ratios of 1.3 and 2.4, respectively. Soda ash did not achieve significant SO_2 removal rates even at a stoichiometric ratio of 4.

A typical curve for outlet SO_2 concentration as a function of time during nahcolite injection is shown in Figure 3-15. The fabric filter cleaning cycle was 3 hours, and during cleaning each of the eight compartments were cleaned for approximately 3 minutes. SO_2 removal at steady state averaged approximately 82 percent, and steady state operation occurred after 2 hours of nahcolite injection.

During the testing at Cameo, KVB observed the effect of temperature at the point of injection for both nahcolite and trona. Both sorbents were injected immediately upstream of the baghouse with flue gas temperatures between 240° and 310°F and into the air preheater at 475° to 500°F.

The effect of decreased baghouse operating temperature (or the temperature at the point of injection) on the initial reaction rate of nahcolite and SO_2 is shown in Figure 3-16. As shown, the initial reaction



Note: Shaded circles represent data obtained from a 1980 test program.

Figure 3-14. Effect of sorbent stoichiometric ratio on SO$_2$ removal.

Source: Muzio, L. J., et al. See Information Sources at the end of this section.

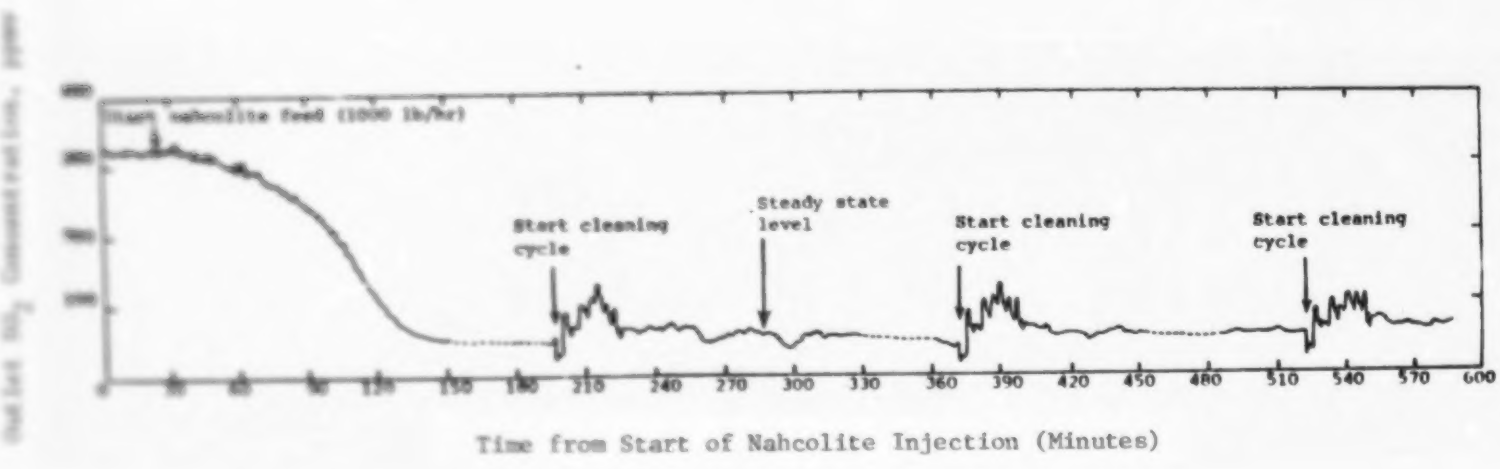


Figure 3-15. Typical curve for SO_2 removal vs. time for nahcolite injection.

16

Source: Muzio, L. J., et al. See Information Sources at the end of this section.

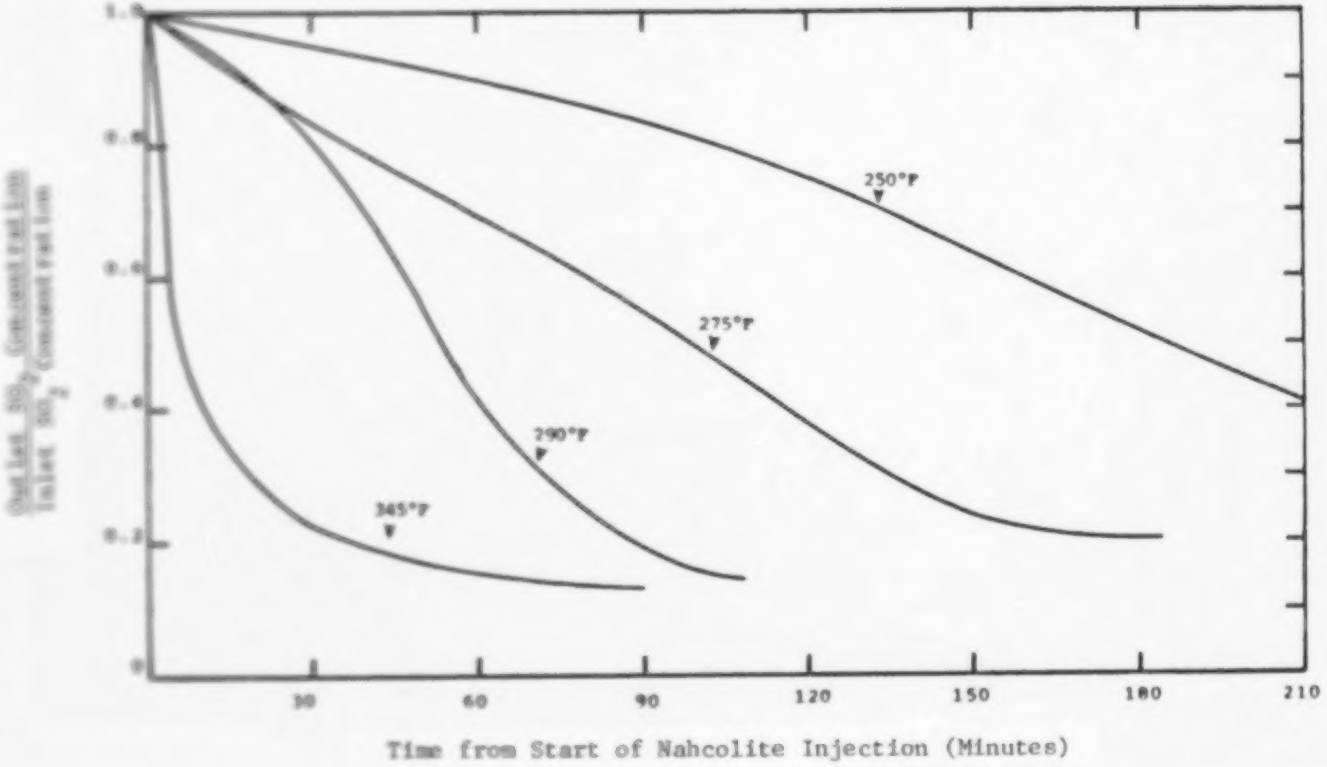


Figure 3-16. Initial reaction rate of nahcolite and SO_2 at different baghouse operation temperatures.

Source: Muzio, L. J., et al. See Information Sources at the end of this section.

rate of nahcolite and SO_2 decreases dramatically as the injection temperature decreases from 345° to 250°F. SO_2 removal with nahcolite was limited to about 40 percent at a stoichiometric ratio of 1.0 and a baghouse temperature of 270°F. By comparison, SO_2 removals near 80 percent were observed at baghouse operating temperatures near 290°F. Injection of nahcolite into the air preheater at temperatures between 475° and 500°F showed average SO_2 removals similar to those obtained for baghouse injection at operating temperatures near 290°F. Decreasing the baghouse temperature did not significantly affect SO_2 removal when nahcolite was injected into the air preheater.

The effect of temperature at the point of injection was found to be somewhat different for trona compared to nahcolite. First, as shown in Figure 3-17, the initial reaction rate of trona and SO_2 is not appreciably affected by a decrease in temperature from 275° to 245°F. Second, injection of trona into the air preheater significantly decreased SO_2 removal compared to injection at lower temperatures upstream of the baghouse. The fact that SO_2 removal with trona is not significantly affected by injection at temperatures in the range of 240° to 290°F is of commercial significance because baghouse operating temperatures will typically decrease at low loads. Trona injection may, therefore, be preferred to nahcolite injection to ensure good SO_2 removal during both low and high load operation.

Baghouse operation and NO_x removal were also evaluated during the dry injection testing. KVB reported that nahcolite dry injection increased the rate of change in flange-to-flange pressure drop by about 20 percent (0.6 in. w.g./hr compared to 0.5 in. w.g./hr with fly ash only). No "appreciable" change in total pressure drop was observed due to trona injection. NO_x removal during the testing ranged from 6 to 16 percent when either nahcolite or trona was used.

Information Sources

Blythe, G. M. and R. G. Rhudy. "EPRI Spray Dryer/Baghouse Pilot Plant Status and Results." (Presented at the 1983 EPA/EPRI FGD Symposium, New Orleans, Louisiana, November 1-4, 1983.)

Parsons, E. L., et al. "SO_2 Removal by Dry FGD." (Presented at the EPA Symposium on Flue Gas Desulfurization, Houston, Texas. October 28-31, 1980.)

Muzio, L. J., et al. (KVB, Inc. and Electric Power Research Institute.) 22 MW Coal-Fired Demonstration of Dry SO_2 Scrubbing With Sodium Sorbent Compounds. Presented at the Second EPRI Conference on Fabric Filter Technology for Coal-Fired Power Plant, Denver, Colorado, March 22-24, 1983.

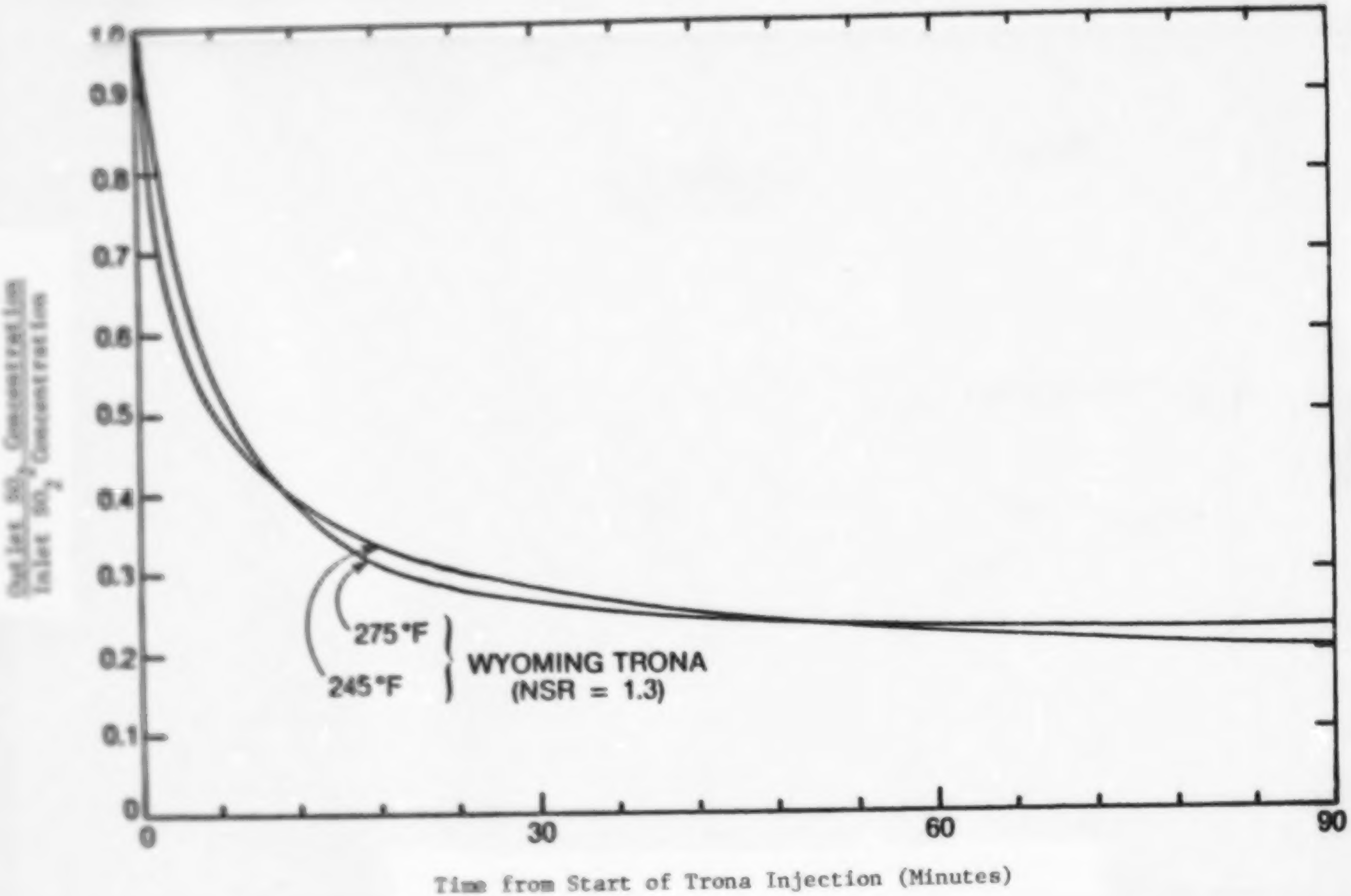


Figure 3-17. The effect of baghouse inlet temperature on the SO_2 removal rate for trona injected upstream of the baghouse.

Source: Muzio, L. J., et al. See Information Sources at the end of this section.

Muzio, L. J., et al. (KVB, Inc. and Electric Power Research Institute.) 22 MW Coal-Fired Demonstration of Dry SO_2 Scrubbing with Sodium Sorbent Compounds. Paper # 83-38.5, presented at the 76th Annual Meeting of the Air Pollution Control Association, Atlanta, Georgia, June 14-24, 1983.

Muzio, L. J., et al. (KVB, Inc.) Dry SO_2-Particulate Removal for Coal-Fired Boilers. Volume 1: Demonstration of SO_2 Removal on a 22-MW Coal-Fired Utility Boiler by Dry Injection of Nahcolite. EPRI CS-2894. Electric Power Research Institute, Palo Alto, California. March 1983.

Muzio, L. J. and T. W. Sonnichsen (KVB, Inc.) Demonstration of SO_2 Removal on a 22 MW Coal-Fired Utility Boiler by Dry Injection of Nahcolite, Trona, and Soda Ash. Volume 2. EPRI Research Project 1682-2. In Press.

Naulty, D. J., et al. (Stearns-Roger Engineering.) Economics of Dry FGD Sorbent Injection. Paper # 83-38.6, presented at the 76th Annual Meeting of the Air Pollution Control Association, Atlanta, June 19-24, 1983.

3.8 EPA/EPRI and EPA

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Background

EPA and EPRI have recently completed performance testing of the spray dryer/fabric filter system at Northern States Power Company's (NSP) Riverside Station under a cooperative funding arrangement. Radian Corporation was the prime contractor for these tests. The primary objective of the program was to quantify SO_2 removal, particulate removal, and lime consumption for the spray dryer/fabric filter system. Preliminary performance and operational results were presented at the EPA/EPRI FGD

Symposium in November 1983 and are summarized briefly in this section. A final report on the testing is currently being prepared with completion scheduled for early 1984.

Spray Drying Demonstration

A simplified flow diagram for the Riverside system is shown in Figure 3-18. This system has been described in detail in several earlier papers presented by Joy/Niro and others. Briefly, however, the nominal 100 MWe spray dryer/fabric filter system has been retrofitted to treat flue gas from two existing boilers (Units 6 and 7). Flue gas is diverted ahead of the existing ESP's, and, after passing through the spray dryer, enters a reverse-air fabric filter. Lime for the system is slaked in either a ball mill or an attrition slaker. The spray dryer, which can treat a maximum gas flow of 680,000 acfm of flue gas at 350°F, has a roof gas disperser, a central gas disperser, and operates with a single rotary atomizer. The design gas flow is a nominal 500,000 acfm, providing a 10-second dryer residence time. Solids collected in the spray dryer and a portion of solids collected in the fabric filter are recycled by direct addition to the feed slurry tank. The Riverside system is normally operated with 35 to 40 percent solids in the slurry fed to the atomizer. Depending on the fresh lime requirements, the amount of recycle is varied to obtain the desired total percent solids in the feed slurry.

Preliminary results available from the EPA/EPRI testing at Riverside basically represent four different operating conditions with two fuels. These four test conditions are shown in Table 3-4. The Sarpy Creek coal/coke fuel mixture has a nominal sulfur content of 1.1 to 1.2 percent and the Illinois coal has a nominal 3.4 percent sulfur content. Low sulfur tests were conducted at both 75 and 90 percent removal. High sulfur tests were conducted at 90 percent removal with and without calcium chloride addition for lime utilization enhancement. All of the tests discussed in this section were conducted with the attrition slaker and at an approach to saturation temperature of 18° to 20°F.

SO_2 removal performance and lime consumption data for Riverside were collected during discrete steady state operating periods. The Riverside Units 6 and 7 are used for peak load periods and were operated only part-time during the testing from July 11 through October 8, 1983. Typical operation involved unit loads of 70 to 90 MWe during the daylight hours, minimum loads (30 to 50 MWe) overnight during the week and banking of the boilers over the weekend. Therefore, although the FGD system operated at desired SO_2 removal levels 24 hours per day, only about 12 hours per week day of nearly full-load operation were available for evaluating system performance.

Preliminary results from the low sulfur testing are shown in Table 3-5. Fabric filter removals shown in Table 3-5 are based on the fabric filter outlet and spray dryer inlet SO_2 concentrations, so that the sum of spray dryer and fabric filter removal equals the overall removal. Recycle ratio

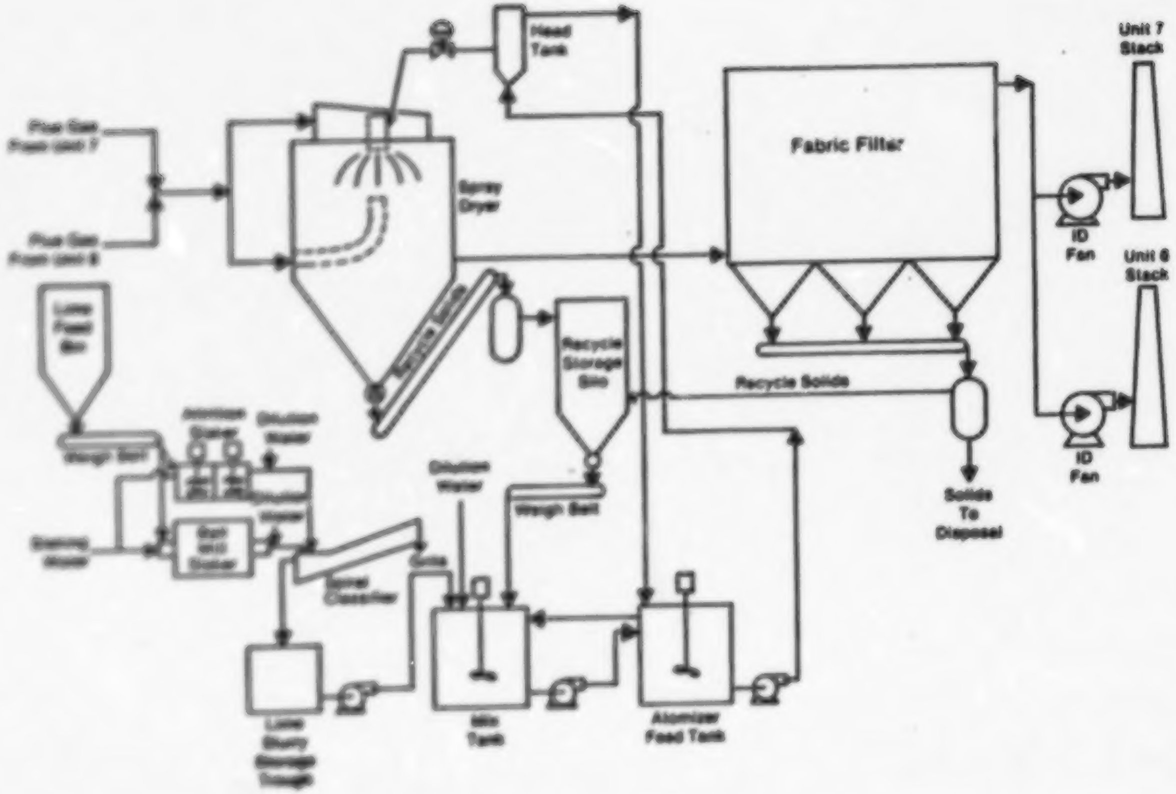
Flue Gas From Unit 7
Flue Gas From Unit 8
Spray Dryer
Head Tank
Fabric Filter
ID Fan
ID Fan
Unit 7 Stack
Unit 8 Stack
Recycle Storage Silo
Recycle Solids
Solids To Disposal
Lime Feed Bin
Weigh Belt
Dilution Water
Slaking Water
Ball Mill Slaker
Spiral Classifier
Grits
Dilution Water
Weigh Belt
Mix Tank
Atomizer Feed Tank
Lime Slurry Storage Tank

Figure 3-18. Simplified flow diagram for Riverside dry FGD system.

TABLE 3-4. OPERATING CONDITIONS FOR PRELIMINARY RESULTS FROM EPA/EPRI RIVERSIDE TESTING

Fuel	SO_2 Removal Level (%)	Fabric Filter A/C Ratio (cfm/ft^2)	Slaker Type	Bag Cleaning Frequency (hours between cleaning)	Approach to Adiabatic Saturation (°F)	Atomizer Feed Weight Percent Solids	Minimum Daytime Boiler Load (MW)
Sarpy Creek Coal/Coke	75	2:1	Attrition	1	18	35	70
Sarpy Creek Coal/Coke	90	2:1	Attrition	1	18	35	70
Illinois Coal	90	2:1	Attrition	1	18	35	70
Illinois Coal[a]	90	2:1	Attrition	1	18	35	70

[a] Calcium Chloride Addition Tests

Source: Blythe, G. M., et al. See Information Sources at the end of this section.

TABLE 3-5. PRELIMINARY SO_2 REMOVAL RESULTS, LOW SULFUR COAL

Nominal SO_2 Removal, %	Spray Dryer Removal, %	Fabric Filter Contribution, %	Reagent Ratio	Recycle Ratio
75	67 - 69	7 - 9	0.6 - 0.7	11:1 - 14:1
90	80 - 81	9 - 10	0.7 - 0.8	9:1 - 13:1

TABLE 3-6. PRELIMINARY SO_2 REMOVAL RESULTS, HIGH SULFUR COAL

Nominal SO_2 Removal, %	Spray Dryer Removal, %	Fabric Filter Contribution, %	Reagent Ratio	Recycle Ratio
90	75 - 77	13 - 15	1.3 - 1.4	2:1 - 3:1
90[a]	67 - 69	22 - 24	0.9 - 1.1	3:1 - 4:1

[a] High calcium chloride concentration tests.

Source: Blythe, G. M., et al. See Information Sources at the end of this section.

was defined as lb recycle material per lb of fresh hydrated lime [$Ca(OH)_2$)]. Low sulfur coal SO_2 removals of 75 and 90 percent were achieved with lower than or stoichiometric amounts of lime. This is attributable to (1) the very high recycle rates possible at 35 percent feed slurry solids and (2) the high alkalinity of the Sarpy Creek coal ash.

High sulfur coal test results are summarized in Table 3-6. For the data corresponding to normal, low chloride operation, reagent ratios between 1.3 and 1.4 were required for 90 percent SO_2 removal. The contribution of the fabric filter to the overall SO_2 removal for the first data set increased in comparison to the low sulfur 90 percent removal case in Table 3-5. The need for a stoichiometric excess of fresh lime is probably a result of the lower recycle ratios for high sulfur operation and the lack of alkalinity in the Illinois coal fly ash.

Chloride addition has been reported by others (see Karlsson, H. T., et al. at the end of this section) to promote increased sorbent utilization in spray dryer-based FGD systems. The benefits are thought to result from the deliquescent properties of calcium chloride, which delay complete drying of the droplets in the spray dryer and result in higher residual moisture levels in the fabric filter solids. The second set of SO_2 removal data in Table 3-6 corresponds to the addition of calcium chloride at levels which result in a chloride content of 1 percent in the fabric filter solids collected. This chloride level in the fabric filter solids was recommended by one of the system vendors, Niro Atomizer, as being an optimum value for lime utilization enhancement, based on pilot-scale studies. At Riverside, this solids chloride level required a liquid phase chloride concentration of approximately 7,500 ppm in the atomizer feed slurry. The results in Table 3-6 show that chloride addition significantly reduced the lime reagent ratio requirements to achieve 90 percent removal. A reduction in lime consumption of approximately 25 percent appeared to occur.

The SO_2 removal results for these high chloride tests show increased SO_2 removal across the fabric filter for 90 percent overall removal. Thus, it appears that the effect of chloride addition on the residual moisture content of the FGD solids has a greater impact on fabric filter SO_2 removal than on spray dryer SO_2 removal. Residual moisture contents in the fabric filter solids increased from just below 1 percent without to nearly 2 percent with chloride addition. This moisture level is still low enough to avoid problems which can result from handling wet solids. Chloride addition had no apparent effect on particulate removal in the fabric filter.

Results from mass loading measurements made during the EPA/EPRI tests are shown in Table 3-7. The results show a 3 to 4 times greater mass loading at the fabric filter inlet compared to the spray dryer inlet. Fabric filter outlet particulate emission rates ranged from 0.002 to 0.012 lb/10^6 Btu, with most values below 0.006 lb/10^6 Btu. This is well below the current NSPS level for utility boilers of 0.03 lb/10^6 Btu.

TABLE 3-7. FLUE GAS MASS LOADING SUMMARY

Sampling Location	Mass Loading (gr/dscf)	
	Low Sulfur Coal Tests	High Sulfur Coal Tests
Spray Dryer Inlet	3.2 to 4.1	2.8 to 4.1
Spray Dryer Outlet	11.0 to 13.8	14.9 to 17.2
Fabric Filter Outlet	0.001 to 0.003	0.001 to 0.008

Source: Blythe, G. M., et al. See Information Sources at the end of this section.

Other results reported for the EPA/EPRI testing at Riverside relate to spray dryer/fabric filter system operability. In general, the Riverside system ran quite well during the testing. None of the problems anticipated for spray dryer systems, such as rotary atomizer wheel pluggage, buildup of wet solids on dryer vessel walls or wetting of fabric filter bag surfaces during upset conditions were observed. However, some problem areas at Riverside appear to be potential sources of problems for other similar dry FGD utility systems. These include typical problems with (1) mixing and pumping slurries with high solids contents, (2) handling large amounts of solids which requires continual equipment maintenance, and (3) sometimes providing adequate atomizer protection during upset conditions.

Future Spray Drying Research

The EPA is currently designing a nominal 2,000-acfm pilot spray drying system for installation at the Industrial Environmental Research Laboratory in Research Triangle Park, North Carolina. The system will use a 7-ft Niro-designed spray dryer with a single rotary atomizer. Particulate collection will take place in either an ESP or a fabric filter. Both pulse-jet and reverse-air fabric filters are being considered. The EPA pilot unit will have continuous recycle capability as well as a gas bypass option. Recycle solids will generally be slurried separately and combined with reagent slurry just upstream of the atomizer. Start-up of the pilot unit is scheduled for Fall 1984.

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Blythe, G. M., et al. "Field Evaluation of a Utility Dry Scrubbing System." (Presented at the 1983 EPA/EPRI FGD Symposium, New Orleans, Louisiana, November 1-4, 1983.)

Karlsson, Hans T., et al., "Activated Wet-Dry Scrubbing of SO_2." Journal of the Air Pollution Control Association. Volume 33, No. 1, January 1983. pp. 23-28.

Machilek, R. M., Acurex Corporation. Personal communication with M. A. Palazzolo, Radian Corporation, March 6, 1984.

3.9 FLAKT, INC.

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Background

Flakt has had three pilot-plant programs; one in Denmark, one in Sweden, and one at Pacific Power and Light's Jim Bridger Station. Most recently Flakt has constructed and tested a 100 MWe demonstration unit at the Jim Bridger Station.

Research and Development

Flakt has completed performance testing on the 100 MWe demonstration unit at the Jim Bridger Station, and no additional testing on the unit is planned. The system was shut down in October 1982 after the completion of 9 months of testing. During the testing the system achieved SO_2 removal design values with sodium carbonate, lime with no solids recycle, and lime with solids recycle. Results of these tests were reported in the previous status report. Briefly, however, the tests showed 88 percent SO_2 removal with soda ash at a reagent ratio of 1.9, 64 percent removal with once-through lime at a reagent ratio of 1.1 and 91 percent removal with lime/recycle at a reagent ratio of 2.2. The tests were conducted with flue gas from firing a 0.6 percent sulfur coal.

Testing on the Jim Bridger demonstration unit was originally scheduled to last 12 months. However, two problems resulted in the test program being stopped earlier. The first problem resulted from the high calcium content of the cooling tower blowdown water used as the source of dilution water. The high calcium content caused scaling of reagent feed piping and plugging of the nozzle atomizers. Periodic cleaning and acid flushing was necessary to maintain reliable system operation.

The second problem resulted from solids re-entrainment in the existing ESP used for particulate collection downstream of the spray dryer. While the opacity of stack emissions was much improved with operation of the spray drying system, reliable particulate emissions data could not be obtained to characterize ESP performance. The collection of representative EPA Method 5 test data was prevented by solids re-entrainment near the outlet sampling location.

Flakt's current R&D efforts are directed primarily at improved atomization and gas/droplet contacting. Flakt is providing a pilot-scale rotary atomizer for studies on an existing spray dryer at the University of Tennessee. The 1,000 acfm contacting chamber is 6 ft in diameter and 10 ft high. The pilot unit has a fabric filter for particulate collection and continuous waste solids recycle capabilities. Current plans are to study droplet size, power consumption, and atomizer reliability with lime. Tests may also be conducted with different types of fly ash (and no lime) to study the effect of fly ash on SO_2 removal.

At their research center in Sweden, Flakt is studying both nozzle and rotary atomizers. Gas flow models are being developed to optimize the placement of multiple nozzles and to assess the effect of spray agglomeration for opposing nozzles. Rotary atomizer studies are in the areas of disk design, power consumption, and droplet size. A new disk atomizer design has been developed that produces small particles with a narrower size distribution than conventional atomizer designs.

Commercial Activities

One of Flakt's two spray dryers at the University of Minnesota has been operational since early November 1983. Performance and compliance test results will not be available until the second-quarter of 1984. The second unit is scheduled for start-up in early 1984.

Flakt has not sold any new spray drying systems since May 1982 when the 520 MWe system was sold to the Grand River Dam Authority's State of Oklahoma Station. Initial operation of this system is scheduled for August 1985.

One of the three spray drying systems (130 MWe) sold by Flakt to a utility in Sodertalje, Sweden has been in operation for about 1 year. The second unit has been operational for 10 months, and the third is expected to be on-line in November 1983. The latest estimated startup date for the 100 MWe system sold to a utility in Malmo, Sweden is early 1984. All of these systems use an ESP for fly ash pre-collection and a fabric filter for collection of FGD waste solids.

Information Sources

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D'Ambrosi, Dennis, Flakt Inc. Telephone conversation with G. S. Shareef, Radian Corporation, December 16, 1983.

3.10 GENERAL ELECTRIC ENVIRONMENTAL SERVICES, INC.

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Background

General Electric (formerly Buell Emission Control, a division of Envirotech Corporation) and the Danish spray dryer firm of Anhydro A/S are currently marketing dry FGD systems in a joint venture. The team has been awarded one utility system (44 MWe) and has sold three industrial units for a single installation.

During the past few years, G.E./Anhydro has conducted EPA-funded dry injection and spray drying demonstration testing at the City of Colorado Springs' Martin Drake Station (see earlier EPA reports on the status of dry SO_2 control systems). The dry injection work was started in October 1979 and completed in 1980. The spray dryer/fabric filter tests began in early 1980 and were completed in June 1981. Test results from the programs have been published in various papers and are being compiled in final reports that should be released in 1984. Most recently, G.E. has developed improved models for spray dryer FGD from the work conducted at Martin Drake. Results of the model development were presented at the EPA/EPRI FGD symposium in November 1983.

Research and Development

G.E. has developed two improved models for predicting SO_2 removal in spray dryer/fabric filter systems and has verified the models with test results from the 8,500-acfm Martin Drake pilot plant. The Martin Drake tests were conducted with lime at inlet SO_2 concentrations ranging from 300 to 600 ppm and 1,000 to 4,000 ppm. High sulfur conditions were simulated by injecting SO_2 and fly ash into a low sulfur coal flue gas slipstream.

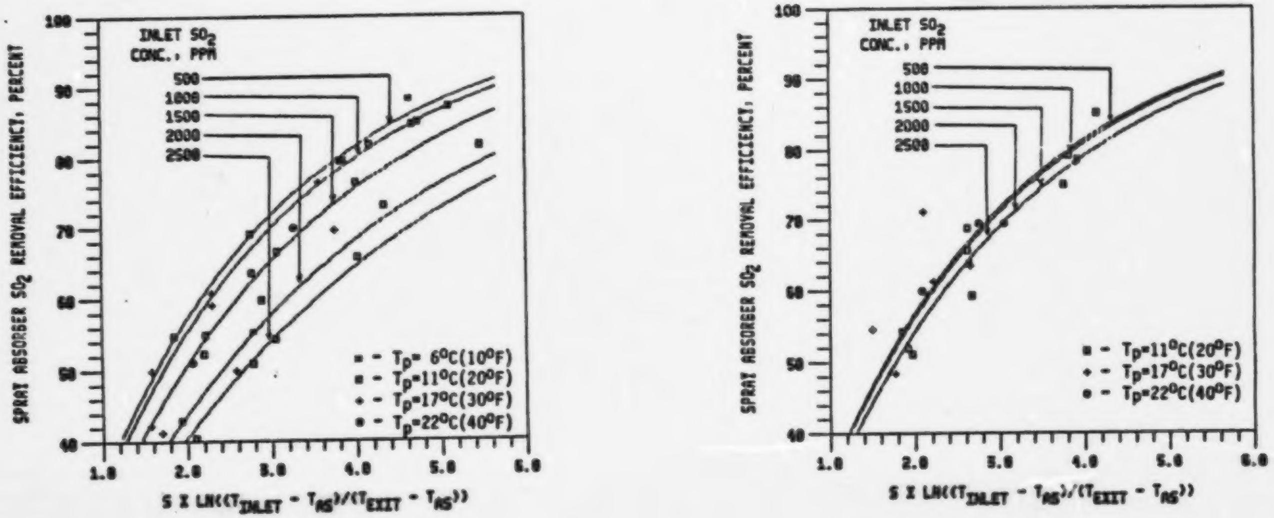
The two models developed by G.E. predict SO_2 removal in the spray dryer only. The first model is an analytical model applicable to once-through lime operation conditions. The second model, an empirical model, extends the analytical model to include the effect of various types of fly ash on SO_2 removal.

A detailed discussion of the theoretical development of the models is too lengthy to include here, but can be found in the Information Sources at the end of this section. All key parameters known to affect SO_2 removal in the spray dryer are accounted for by the models, including:

- approach to saturation temperature,
- reagent ratio,
- feed slurry solids content,
- inlet SO_2 concentration,
- gas inlet temperature,
- gas inlet moisture content,
- droplet diameter,
- fly ash recycle, and
- fly ash type.

For the once-through model, G.E. found good agreement (correlation coefficients better than 0.9) between measurements and the theoretical model predictions for SO_2 removal at various inlet SO_2 concentrations as shown in Figure 3-19a. Both the measurements and the model showed improved once-through SO_2 removal performance for decreasing inlet SO_2 concentrations over the 2,500 to 1,000 ppm range. G.E. suggests that the decreased removal may be a result of a reduced droplet evaporation time at the higher inlet SO_2 concentrations. The solids content of the droplets increases with higher inlet SO_2 for a fixed reagent ratio and approach to saturation. For inlet SO_2 concentrations in the 0 to 1,000 ppm range, both the model and the test results indicated little effect of inlet concentration on SO_2 removal performance.

The theoretical (once-through) model was also compared by G.E. with the results of solids recycle tests (Figure 3-19b). For these tests, recycle solids consisted of Martin Drake flyash and spray dryer product. The model and the data again agreed fairly well. With solids recycle, however, both the model predictions and the data showed no dependence of SO_2 removal performance on inlet SO_2 concentration.



(a). Theoretical model correlations for once-through operating mode.

(b). Theoretical model correlations for solids recycle operation.

Note: S = reagent ratio; T_{AS} = adiabatic saturation temperature , °F; (°F)
T_P = approach to adiabadic saturation temperature , °F

Figure 3-19. Comparison of G.E. pilot spray dryer SO_2 removal data with predicted curves from a theoretical model.

Source: Samuel, E. A., et al. See Information Sources at the end of this section.

Martin Drake data for the injection of different types of flyash were correlated using the empirical model. The types of fly ash included Martin Drake, Texas lignite, and eastern coal fly ash. The correlations, which are shown in Figure 3-20, include once-through as well as solids recycle data for all combinations of inlet SO_2 concentration, stoichiometric ratio, and approach to saturation. The enhancement of SO_2 removal efficiency with recycle was found to be lowest for the Martin Drake fly ash (Colorado Coal) and highest for the eastern coal fly ash.

Commercial Activities

In mid-1983, G.E. sold three new industrial spray dryer/fabric filter units for the Puget Sound Naval Shipyard in Bremerton, Washington. Each unit will treat 67,000 acfm of flue gas at 350°F from a single coal-fired boiler (140,000 lb/hr of steam). The fuel for the boiler is a maximum 1.6 percent sulfur coal.

Each spray dryer, 28 feet in diameter and equipped with a single rotary atomizer, will be followed by a reverse-air fabric filter. The system is guaranteed for an SO_2 removal of 84 percent and an outlet particulate emission level of 0.03 lb/10^6 Btu. No solids recycle will be used.

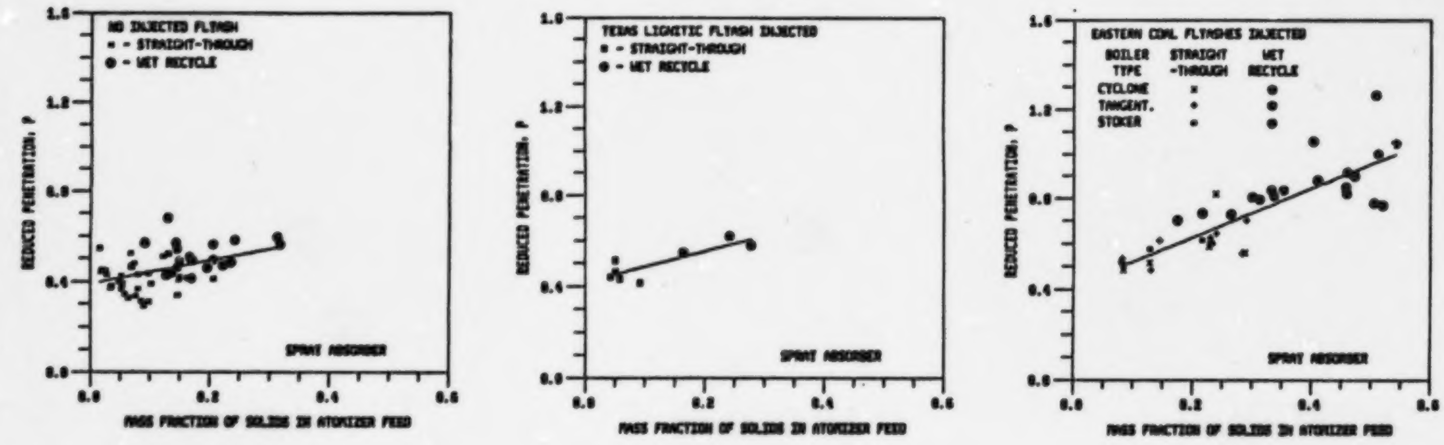
The 44 MWe system at the Marquette (Michigan) Board of Light and Power Shiras Station is currently operational following startup in May 1983. The system has not yet been turned over to the utility for commercial operation.

The spray dryer/fabric filter system at the Shiras Station treats flue gas from a pulverized coal-fired boiler burning a maximum 1.5 percent sulfur subbituminous coal. The spray dryer, equipped with a single, belt-driven rotary atomizer, is followed by an eight compartment reverse-air fabric filter. The spray dryer is designed to collect 40-55 percent of the spray-dried solids with the remainder collected in the fabric filter. Recycle solids and reagent are slurried separately and combined in the "dual feed" rotary atomizer. Flue gas exiting the spray dryer is reheated by hot gas bypassed around the spray dryer from upstream of the air preheater.

Compliance tests were conducted on the Shiras system in September 1983. Results of three EPA Method 6 tests showed an average SO_2 removal efficiency of 87.3 percent at a reagent ratio of approximately 1.2 and an approach to saturation of 40°F. The boiler fired a 0.5 percent sulfur coal. The compliance tests were conducted prior to full system optimization and without solids recycle. Additional testing with solids recycle and at a closer approach to saturation is planned for Spring 1984.

Information Sources

Galli, B., G. E. Environmental Services. Telephone conversation with M. A. Palazzolo, Radian Corporation, July 16, 1983.



Note: For the **empirical** model, P = uF + x, where
u = an empirical constant varying with fly ash type; x = a constant;
F = mass fraction of solids in atomizer feed.

Figure 3-20. Correlation of Martin Drake pilot data with empirical model for once-through and recycle operation with injection of various types of fly ash.

Source: Samuel, E. A., et al. See Information Sources at the end of this section.

Fortune, O., et al. "Design and Initial Operation of the Spray Dry FGD System at the Marquette, Michigan Board of Light and Power Shiras #3 Plant." (Presented at the 1983 EPA/EPRI FGD Symposium, New Orleans, Louisiana, November 1-4, 1983.)

Samuel, E. A., et al. "Process Characterization of SO_2 Removal in Spray Absorber/Baghouse Systems." (Presented at the 1983 EPA/EPRI FGD Symposium, New Orleans, Louisiana, November 1-4, 1983.)

Fortune, O., G. E. Environmental Services. Telephone conversation with M. A. Palazzolo, Radian Corporation, February 28, 1984.

3.11 JOY/NIRO

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Background

Joy/Niro conducted several pilot- and demonstration-scale development programs and operated the 110 MWe system at the Northern States Power Company (NSP) Riverside Station for 15 months in 1981 and 1982. The team has recently announced the development of a new spray drying process for simultaneous SO_x/NO_x removal.

Joy/Niro has been awarded contracts for 10 utility commercial spray drying systems and nine industrial units (one of which is being applied to a carbon regeneration furnace). Two of the utility systems and six of the industrial units are now operational and the third utility system is currently in start-up. In addition, the Riverside demonstration unit is now being operated by NSP.

Joy/Niro's research and development and commercial activities are discussed in this section.

Research and Development

Joy/Niro conducts the bulk of their basic research work using a 5,000-acfm pilot system located at Niro's Copenhagen facilities. This system is also used extensively to gather site-specific data required to prepare bids for commercial systems. Joy/Niro has emphasized in the past that site-specific factors such as coal and fly ash characteristics are important enough in bid preparation and system design to warrant pilot-scale testing of the process with the specific coal that will be used. Coal and ash characteristics can significantly impact fresh reagent requirements and are also likely to be a major factor in the design and operation of the fabric filter or ESP.

Joy/Niro has recently announced the development of a new spray drying process for simultaneous NO_x and SO_2 removal. The process uses the same equipment as other Joy/Niro dry FGD systems but achieves 90-95 percent SO_2 removal and 50-60 percent NO_x removal. Removal of NO_x is obtained by adding NaOH to the atomizer feed slurry at a rate of approximately 10 percent by weight of the lime feed rate. The fabric filter is then operated within a critical temperature range or "thermal window." This temperature range, which is illustrated by bench-scale data in Figure 3-21, is from 195° to 215°F. The bulk of the SO_2 removal occurs in the spray dryer and the NO_x and remaining SO_2 removal occurs in the fabric filter.

In addition to the thermal window, another parameter the Joy/Niro team has identified as important to the SO_x/NO_x process is the ratio of SO_2/NO_x entering the spray dryer. The SO_2/NO_x ratio should preferably be 1 (one) or greater. The effect of this ratio is illustrated by the bench- and pilot-scale test results in Table 3-8. As shown in the table, the highest NO_x removals are obtained at the higher SO_2/NO_x ratios.

Joy/Niro has demonstrated their new NO_x/SO_x process on pilot, industrial, and utility scales with similar results. The pilot plant results are shown in Table 3-9. In April 1983, Joy/Niro conducted demonstration testing of the SO_x/NO_x process on the industrial spray drying system at Argonne National Laboratory. The Argonne system treats flue gas from a 170,000 lb steam/hr stoker boiler firing high sulfur (3.0-3.5 percent) Illinois coal. Results of these tests, which are presented in Table 3-10, show an SO_2 removal of 95 percent and an NO_x removal of 55 percent at a lime reagent ratio of 1.3. During October and November 1983, Joy/Niro conducted a 3-week test series on the new NO_x/SO_x process with the 110 MWe unit at Northern States Power's Riverside Station. Results from this test series are not yet available, but reportedly verify the pilot and industrial scale findings.

TABLE 3-8. EFFECT OF SO_2/NO_x RATIO ON NO_X REMOVAL

Scale of Test	Inlet SO_2 Level PPM	Inlet NO_x Level PPM	SO_2/NO_x Ratio	NO_x Removal %
Bench[a]	0	300	0	0
Bench	100	300	0.3	34
Bench	300	300	1	70
Pilot[b]	1000	300	3.3	40
Pilot	1600	300	5.3	50
Pilot	2500	300	8.3	65

[a] Performed on fixed-bed reactor with layer of reactive powder.

[b] Conducted on Niro's pilot plant in Copenhagen.

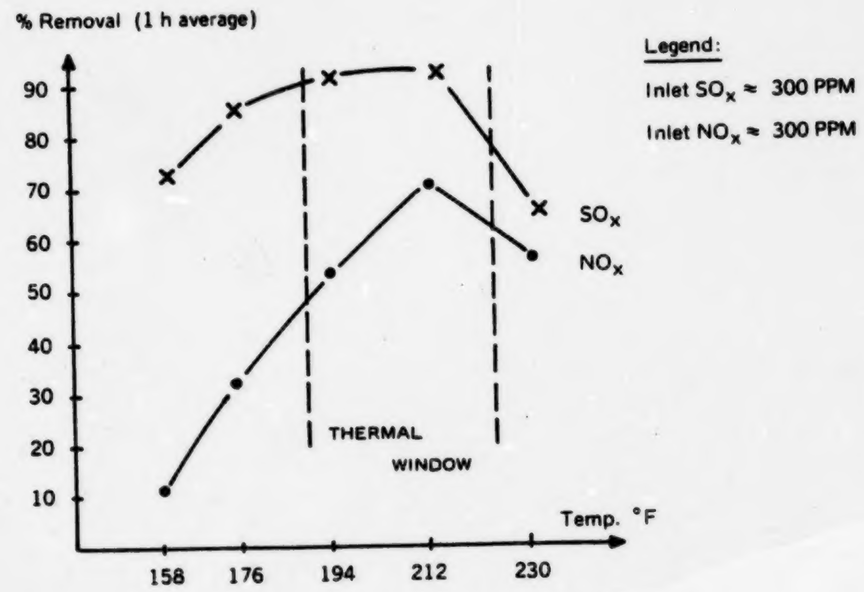

Figure 3-21. Influence of reaction temperature on SO_x/NO_x reaction.

Source: Felsvang, K. and P. Morsing. See Information Sources at the end of this section.

TABLE 3-9. PILOT PLANT TEST RESULTS FOR SO_x/NO_x PROCESS ON HIGH SULFUR COAL

% Solids in Feed Slurry			34	30	37
Inlet SDA	Temp.	°F	371	336	334
	SO_x	PPM dry	2814	2762	2638
	NOx	PPM dry	310	309	346
Inlet BH	Temp.	°F	188	222	204
% NO_x Removal			65.5	62.5	57.2
% SO_x Removal			98.8	86.2	93.3
Lime Stoichiometry			1.44	1.10	1.20

Source: **Felsvang**, K. and P. Morsing. See International Sources at the end of this section.

TABLE 3-10. RESULTS OF SO_2/NO_x PROCESS DEMONSTRATION AT ARGONNE

	Scrubber									
	Inlet				Outlet	Bagfilter Outlet		Results		
Mode of Operation	PPM SO_2	PPM NO_x	Temp. °F	Gas-Flow lb/h	Temp. °F	PPM SO_2	PPM NO_x	% Removal SO_2	% Removal NO_x	Stoichiometry for Lime
Normal SO_2 Removal Only	1800	290	335	200,000	148	90	281	95	3	1.4
SO_x/NO_x Mode	1500	280	330	140,000	195	60	126	95+	55	1.3

Source: Felsvang, K. and P. Morsing. See Information Sources.

Characterization studies on the waste product from the SO_x/NO_x process have been completed and are discussed in detail in Section 4. Based on leachate tests, the waste product would be classified as non-toxic under RCRA regulations. The composition of waste products from NO_x and SO_2 removal and SO_2 removal only are compared in Table 3-11. Key differences between the two wastes are (1) the presence of sodium sulfite and calcium nitrate, and (2) the significantly higher ratio of calcium sulfate to calcium sulfite in the NO_x/SO_2 waste product.

Joy/Niro operated the 110 MWe demonstration system at Riverside for 9 months during 1981 and approximately 6 months during 1982. The Riverside Station was tested under EPA/EPRI funding in the summer of 1983 and a brief description of the system is given in Section 3.6. Results from parametric and demonstration tests at Riverside were discussed in the previous status report and in several papers presented by Joy/Niro. An overview of test results from 1981 and 1982 was presented at the 1983 EPA/EPRI FGD symposium, and some of the results presented in the paper are discussed below.

A total of 164 parametric tests were conducted by Joy/Niro and Northern States Power at the Riverside Station in 1981 and 1982. In addition, five sets of demonstration tests were made of 5 to 10 days duration each. Data were collected on the five fuels listed in Table 3-12, which include both low and high sulfur coals. SO_2 removal is shown in Figure 3-22 as a function of reagent ratio and approach temperature for all 164 tests. The curves shown in the figure for approach temperatures of 18° and 40°F were generated using a multiple linear regression analysis. These approach temperatures represent typical low and high design approach temperatures for utility systems.

Commercial Activities

Joy/Niro was awarded two new utility spray drying systems since mid-1983 and sold three new industrial spray drying units in 1983. The status of Joy/Niro's commercial systems are shown in Table 3-13. One recent utility system award was for a 710 MWe system at Central and Southwestern Services' Coleto Creek Station. This lime-based system will consist of four spray dryers followed by an electrostatic precipitator (ESP) and will treat flue gas from a 0.4 percent sulfur subbituminous coal. In December 1983, Joy/Niro was awarded a contract for an existing 330 MWe boiler at Pacific Power and Light's Wyodak Station. This lime-based system will consist of three spray dryers followed by an existing ESP and will also treat flue gas from a 0.4 percent sulfur subbituminous coal. Both the Coleto Creek and Wyodak systems will use solids recycle and warm gas bypass.

The industrial units sold to Malmstrom Air Force Base will treat flue gas from three boilers producing 90,000 lb/hr of hot water each. The fuel for the boilers is a 1 percent sulfur western subbituminous coal. Each boiler will have a single spray dryer, equipped with a rotary atomizer, followed by a reverse-air fabric filter. Solids recycle will be used.

TABLE 3-11. CHEMICAL COMPOSITION (wt%) OF THE WASTE PRODUCED FROM SO_2 and COMBINED SO_2/NO_x SYSTEMS

Component	Chemical Composition (wt%)	
	SO_2 Removal	SO_2/NO_x Removal
Sulfite as $CaSO_3 \cdot \frac{1}{2}H_2O$	59	16
Sulfate as $CaSO_4 \cdot 2H_2O$	16	43
Nitrate as $Ca(NO_3)_2$	∿ 0	3
Excess Alkalinity as $Ca(OH)_2$	15	21
Ash & Inerts	9	8
Moisture	1	1
Na_2SO_3	∿ 0	9

Source: Felsvang, K. and P. Morsing. See Information Sources at the end of this section.

TABLE 3-12. TYPICAL PROPERTIES OF COALS AND FUEL BLENDS BURNED AT RIVERSIDE DURING 1981 AND 1982

Fuel	Heating Value lb/MBtu	Ash Content per cent	Sulfur Content per cent
Colstrip	8,700	8.3	0.8
Colstrip/Coke	9,200	6.7	1.2
Sarpy Creek	8,300	10.8	0.8
Sarpy Creek/Coke	9,200	8.9	1.2
Illinois	10,900	10.4	3.2

Source: Gustke, J. M., et al. See Information Sources at the end of this section.

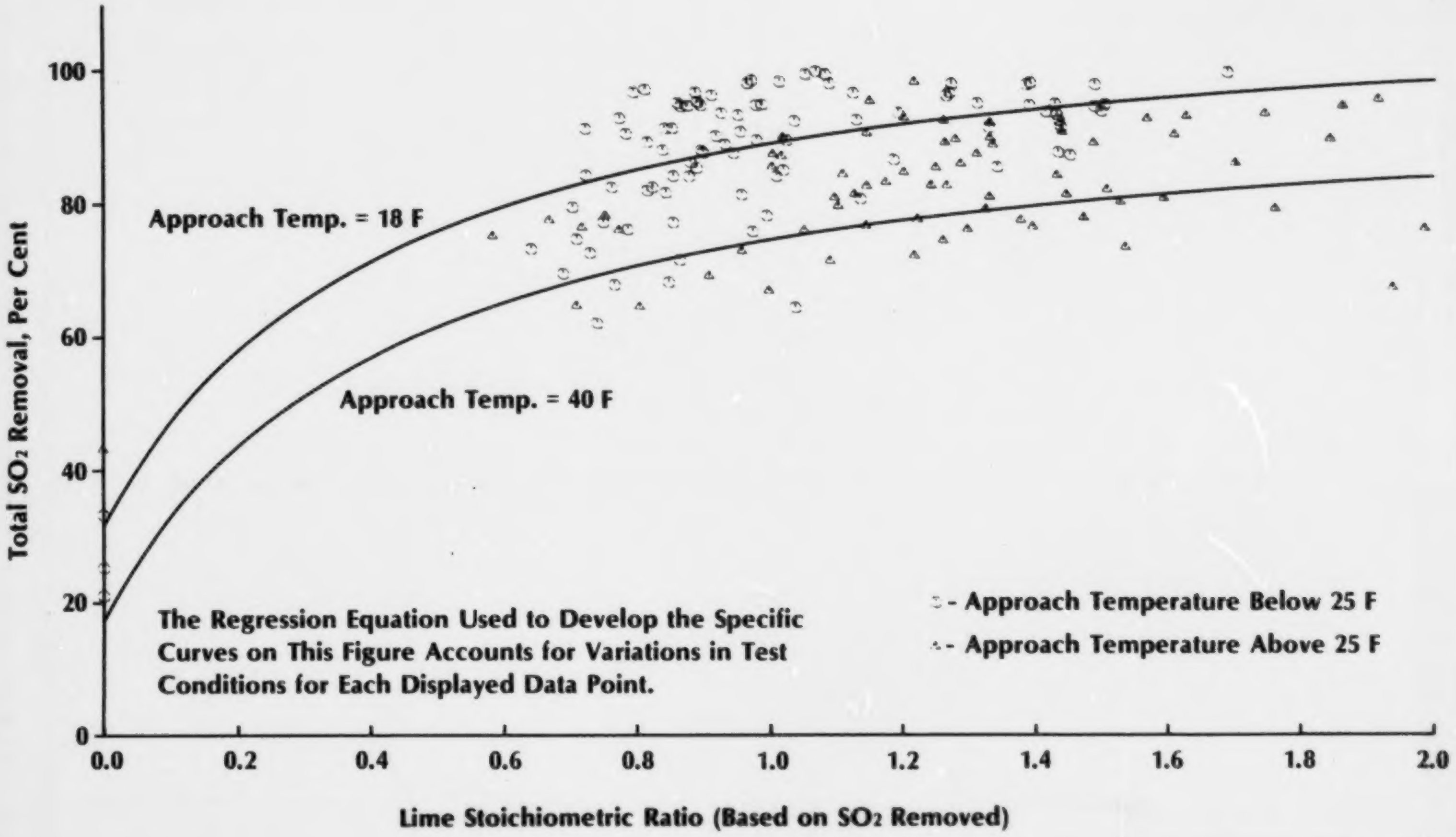

Figure 3-22. Overall SO_2 removal vs. stoichiometric ratio for 164 tests at Riverside.

Source: Gustke, J. M., et al. See Information Sources at the end of this section.

TABLE 3-13. STATUS OF JOY/NIRO COMMERCIAL SPRAY DRYING SYSTEMS (MARCH 1984)

System Purchaser	Location	Size	Status/Startup Date
Basin Electric	Antelope Valley, Unit 1 (Beulah, ND)	440 MWe	Operational; turned over to the utility.
Basin Electric	Antelope Valley, Unit 2 (Beulah, ND)	440 MWe	April 1985
Tucson Electric	Springerville, Unit 1 (Springerville, AZ)	350 MWe	June 1985
Tucson Electric	Springerville, Unit 2 (Springerville, AZ)	350 MWe	June 1987
Platte River Power Authority	Rawhide, Unit 1 (Fort Collins, CO)	280 MWe	Initial startup stages (December 1983)
Sunflower	Holcomb, Unit 1 (Holcomb, KS)	319 MWe	Operational; has not yet been turned over to the utility.
Northern States Power Company	Sherburne County, Unit 3 (Becker, MN)	860 MWe	1990
Cajun Electric	Oxbow, Unit 1 (Coushatta, LA)	565 MWe	Projected for 1989 but need for system being re-evaluated
Central and Southwestern Services	Coleto Creek, Unit 1 (Corpus Christi, TX)	710 MWe	1988
Pacific Power and Light	Wyodak, Unit 1 (Gillette, Wyoming)	330 MWe	Fall 1986
Argonne National Lab	(Argonne, IL)	170,000 lb steam/hr	Operating; turned over to Argonne
GM-Buick Motors Division	(Flint, MI)	450,000 lb steam/hr	Operating, has not yet been turned over to GM-Buick
Fairchild Air Force Base	Units 1, 2, 3 (Spokane, WA)	110,000 lb steam/hr each	Operating, has not yet been turned over to Fairchild
Malmstrom Air Force Base	Units 1, 2, 3 (Great Falls, MT)	90,000 lb/hr hot water each	Spring 1985
Calgon (incinerator application)	(Catlettsburg, KY)	--	July 1982

The 440 MWe Joy/Niro spray drying system on Basin Electric's Antelope Valley Unit 1 became operational in May 1983. This system, which consists of five spray dryers and two reverse-air fabric filters, has passed initial performance tests, achieving SO_2 removals of 64, 81, and 92 percent at reagent ratios of approximately 0.5, 0.9, and 1.1, respectively. Preliminary results of performance tests conducted in September 1983 are compared with guarantee conditions in Table 3-14. Testing and development planned for early 1984 will focus on maximizing lime utilization and minimizing spray dryer and fabric filter pressure drop. Further testing of the system will also be conducted at 81 and 89 percent SO_2 removal conditions. Commercial operation of Antelope Valley Unit 1 is scheduled for July 1984.

Joy/Niro's utility system at Sunflower Electric and the industrial systems at GM-Buick Motors and Fairchild Air Force Base all became operational in mid- to late-1983. Performance testing of these systems is currently scheduled for early 1984. Platte River's Rawhide Unit 1 system is currently in the early stages of startup.

The 110 MWe system at the Riverside station is now being operated by Northern States Power Company. Results from operation and recent EPA/EPRI-funded process tests on this system are discussed in Section 3.6. The Argonne National Laboratory system, which has been operating since December 1, 1981, has also been turned over to the system purchaser. Recent performance tests conducted on the Argonne system are discussed in Section 3.4.

Future Activities

Joy/Niro currently has several utility and industrial system bids outstanding. Two of the industrial systems should be awarded within the next 4 to 5 months. Regarding the spray drying FGD market, a Joy/Niro spokesman indicated that activity is improving with the current economic upturn, and the long-term outlook is very promising if the current U. S. interest in controlling acid rain is consumated.

Joy/Niro is continuing the development of their NO_x/SO_x process and also plans to conduct testing with "alternate reagents for SO_2 removal" in late 1983.

Information Sources

Erikson, R. L., et al. "Startup and Initial Operating Experience of the Antelope Valley Unit/Dry Scrubber." (Presented at the 1983 EPA/EPRI FGD Symposium, New Orleans, Louisiana, November 1-4, 1983.)

Felsvang, Karsten and Per Morsing. "Acid Rain Prevention Through New SO_x/NO_x Dry Scrubbing Process." (Presented at the 1983 EPA/EPRI FGD Symposium, New Orleans, Louisiana, November 1-4, 1983.)

TABLE 3-14. PRELIMINARY RESULTS OF PERFORMANCE TESTS AT ANTELOPE VALLEY UNIT 1

Parameter	Test Result	Guarantee
SO_2 removal, %	64	62
Inlet, SO_2, ppm	655	800
Outlet, SO_2, ppm	220	304
Outlet, SO_2, lb/hr	2,973	3,844
Reagent Ratio (for 64% removal)	0.47	-
Reagent Ratio (corrected to 62% removal)	0.45	0.54
Outlet Particulate, gr/dscf	0.0025	0.012
Outlet Particulate, lb/hr	24	210
Total Pressure Drop, in. W.G.	15.0	13.4
Power Consumption, kW	2,341	2,757
Reheat Bypass, 10^6 Btu/hr	7.1	7.2
Approach to Saturation, ^oF	29	-
Solids in Atomizer Slurry, %	41	-
Baghouse Outlet, ^oF	189	184

Source: Erikson, R. L., et al. See Information Sources at the end of this section.

Gustke, J. M., et al. "Overview and Evaluation of Two Years of Operation and Testing of the Riverside Spray Dryer System." (Presented at the 1983 EPA/EPRI FGD Symposium, New Orleans, Louisiana, November 1-4, 1983.)

Sharp, Ron, Niro Atomizer, Inc. Telephone conversation with M. A. Palazzolo, Radian Corporation, July 27, 1983.

Kaplan, Steven, Niro Atomizer, Inc. Telephone conversation with M. A. Palazzolo, Radian Corporation, December 12, 1983.

Kaplan, Steven, Niro Atomizer, Inc. Letter and attachments to M. A. Palazzolo, Radian Corporation, March 2, 1983.

3.12 MIKROPUL CORPORATION/KOCH PROCESS SYSTEMS, INC.

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Background

MikroPul is a division of U. S. Filter, which includes Ducon, a wet scrubber manufacturer. MikroPul began work on a spray dryer-based FGD system in January 1978. As a result of their work, MikroPul was awarded a contract in late 1978 to provide a spray dryer/fabric filter system for a coal-fired industrial boiler at Strathmore Paper Company at Woronoco, Massachusetts. MikroPul established a working relationship with Koch Engineering in 1979. Koch Engineering successfully implemented a redesign of the spray dryer internals at Strathmore to improve SO_2 removal efficiency and solve problems with frequent wetting of the spray dryer walls. As a result of the working relationship developed between MikroPul and Koch Engineering during the Strathmore modifications, the two companies have agreed to market dry FGD systems jointly. Koch Engineering has been developing spray dryer FGD technology since early 1979. Recently, however, responsibility for dry scrubbing has been given to its subsidiary, Koch Process Systems.

Research and Development Activities

Koch Process Systems' R&D work is currently being conducted at Abcor, Inc. in Wilmington, Massachusetts. Abcor is a wholly owned subsidiary of Koch Engineering. The Abcor facility has a 5 million Btu/hr pulverized coal-fired boiler. Gas flow from the boiler is approximately 2,000 acfm at 350°F (with 40 percent excess air). The facility has two pilot-scale spray dryers, a 40-in. diameter dryer equipped with a two-fluid nozzle atomizer and a 60-in. diameter dryer equipped with a rotary disc atomizer. In addition, the facility is equipped with a pulse-jet fabric filter and has the capability to test different coal types, solids recycle, and flue gas bypass.

On-going research at Abcor is focussed in the areas of atomization, solids recycle, and potential incinerator spray drying applications. The atomization studies relate primarily to a comparison of rotary and nozzle atomizers through a comparison of particle or droplet size, size distribution, and spray patterns for the two atomization techniques. No results from these studies have as yet been published.

The solids recycle testing is being conducted to develop an in-house data base on the effect that solids recycle has on lime reagent requirements. These tests are being conducted with fly ash from a wide variety of coals.

The final area of on-going research at Abcor relates to hazardous and municipal solid waste incineration. Koch is currently studying the applicability of spray drying technology to the control of SO_2 and HCl emissions from these incinerators.

Commercial Activities

MikroPul/Koch's 40,000 acfm spray dryer/fabric filter system at Strathmore Paper Company has now been operational for more than 3 years. Overall FGD system availability during this period has been in excess of 97 percent.

Information Sources

Biedell, Edward, MikroPul Corporation. Telephone conversation with M. A. Baviello, Radian Corporation. October 20, 1983.

Steward, Mike, Koch Process Systems. Telephone conversation with M. A. Palazzolo, Radian Corporation. November 19, 1983.

3.13 PUBLIC SERVICE COMPANY OF COLORADO

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Planned Dry Injection System

The first planned commercial application of dry injection technology has been announced by Public Service Company of Colorado (PSCC) for a 500 MWe unit. The plant will be located in Morgan County, Colorado and is scheduled for start-up in 1990. The system, which will use trona ore as the sorbent, will be designed by PSCC to achieve 70 percent SO_2 removal on a 0.4 percent sulfur western coal. The trona will be injected just upstream of the fabric filter into flue gas at approximately 132° to 138°C (270° to 280°F).

The Public Service of Colorado has already contracted with several companies to obtain trona ore. The power plant is conveniently located within 400 miles of both trona mines and potential nahcolite mines.

The solid waste from this dry injection system will be disposed of in an on-site, clay-and-plastic-lined landfill. Monitoring wells installed around the landfill will be able to detect the formation of leachate that may contaminate groundwater. However, the company feels confident that the landfill design will adequately protect groundwater.

Information Sources

Green, George. Public Service Company of Colorado. Telephone conversation with M. A. Palazzolo, Radian Corporation. July 27, 1983.

3.14 ROCKWELL INTERNATIONAL

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Background

The former Rockwell International/Wheelabrator-Frye joint venture sold two commercial systems: a utility system to Otter Tail Power Company (Coyote Station) for a 410 MWe utility boiler and a 65,000 acfm industrial system to Celanese Fibers Company. Both are spray dryer/fabric filter systems.

Since the dissolution of the joint venture in early 1980, both Rockwell and Wheelabrator-Frye have continued to be involved in dry FGD projects. Rockwell has been awarded a contract for a commercial spray drying system to serve Sierra Pacific Power's North Valmy Station.

Research and Development Activities

Rockwell's mobile pilot plant has been moved to TVA's Shawnee Station to study high sulfur coal applications. Some preliminary results using 3.5 percent sulfur coal indicate an SO_2 removal rate of 90 percent with inlet SO_2 concentrations up to 3,000 ppm. This was achievable at a reagent (lime) ratio approaching 1.3. Rockwell is still optimizing this system.

In addition to the work at TVA, Rockwell is also conducting in-house studies on rotary atomizers. Some of these studies relate primarily to improving the mechanical design of the atomizer, while others involve optimizing spray patterns and gas-slurry contacting through studies on droplet size and droplet size distribution. Rockwell is also conducting waste characterization studies for dry FGD systems.

In October 1983, the company decommissioned its pilot plant at Commonwealth Edison's Joliet Station. There are currently no plans to install this pilot plant at a different location.

Commercial Activities

The joint venture Rockwell/Wheelabrator-Frye sodium-based system at Coyote Station was turned over to Montana-Dakota Utilities for operation following performance tests conducted in August 1982. Earlier test results for this system were reported in the last status report.

The other joint venture dry FGD system at Celanese Fibers' Amcelle Plant began operation in January 1980. System availability averaged between 90 and 95 percent for the period from October 1980 to mid-1982. This system is currently not being operated because of a low steam demand and the availability of low sulfur (compliance) coal.

Rockwell has not sold any new spray drying systems since the 270 MWe system was sold to Sierra Pacific Power for use on its North Valmy Station. This system is due to start up in early 1985.

Information Sources

Gehri, Dennis, Rockwell International. Telephone conversation with M. A. Baviello, Radian Corporation. October 18, 1983.

Goland, Yaacov, Rockwell International. Telephone conversation with M. A. Baviello, Radian Corporation. October 18, 1983.

3.15 UNIVERSITY OF NORTH DAKOTA ENERGY RESEARCH CENTER

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Background

The University of North Dakota Energy Research Center (UNDERC) is now responsible for the dry injection research activities that had been conducted by DOE's Grand Forks Energy Technology Center. UNDERC is managed by the Grand Forks Project Office of DOE.

Under a DOE flue gas cleanup program, the center had conducted dry injection research on a 130-scfm system that compared nahcolite and trona sorbents. The center also completed limestone injection studies at Otter Tail Power Company's Hoot Lake Station.

Research and Development Activities

The University of North Dakota Energy Research Center has recently conducted lime and limestone injection studies with a propane-fired 130-scfm combustion system and a baghouse with ceramic filters. The sorbents were injected into flue gas at elevated temperatures (up to 2,900°F). SO_2 removals of 30 and 40 percent were obtained with quick lime and hydrated lime, respectively at Ca/S ratios of 1.0. Lower SO_2 removals (approximately 5 to 10 percent) were obtained with limestone.

Both the flue gas temperature and the baghouse temperature were varied in the injection studies. The optimum flue gas temperature for SO_2 removal ranged from 2,700°F to 2,900°F. The high temperatures were needed because of the short residence time in the flue gas system.

The baghouse temperature was varied from 200°F to 1,000°F. The optimum temperatures ranged from 900°F to 1,000°F. At this high temperature, 10 to 11 percent of the total SO_2 removal was achieved in the baghouse.

Because of a design problem, the seams of the ceramic filters used in the baghouse opened up during the initial dry injection tests. UNDERC recently installed new filters with oversewn seams. No scan problems have occurred with the new filters. UNDERC will use seamless filters in the near future.

UNDERC has begun to develop a technology that combines hydrated lime injection with ammonia once-through catalyst reduction to remove SO_2, NO_x, and particulates. A pressure hydrator will inject the hydrated lime into the flue gas. Results from this testing are not available at this time.

Information Sources

Weber, Greg, University of North Dakota Energy Research Center. Telephone conversation with M. A. Baviello, Radian Corporation. October 24, 1983.

3.16 WHEELABRATOR-FRYE, INC.

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Background

The Wheelabrator-Frye/Rockwell International venture sold two commercial systems: a 410 MWe utility system to Otter Tail Power Company (Coyote Station) and a 65,000 acfm industrial system to Celanese Fibers Company. Both are spray dryer/baghouse systems.

Wheelabrator-Frye and Rockwell dissolved their joint venture in January 1980, but both continue to be involved in dry scrubbing projects. Wheelabrator-Frye has since sold an industrial spray drying system to the Austell Box Board Corporation. In February 1983, Wheelabrator-Frye was merged with the Signal Companies.

Research and Development Activities

Wheelabrator-Frye is continuing its research on two-fluid nozzles and rotary atomizers and the dry scrubbing process. The design and operation of the nozzle atomizer is being refined based on experience from the Austell system which began operation in early 1983. A rotary atomizer with a 400-hp capability is also being developed. Additional studies relate to the optimization of the spray dryer process through the improvement of atomizer design, and scale model studies of gas patterns in rotary atomizer and two-fluid nozzle spray chambers.

Based on a recent economic study, Wheelabrator-Frye generally recommends two-fluid nozzles rather than rotary atomizers for systems less than 170,000 acfm with an SO_2 removal requirement of 70 percent. Data comparing the costs of nozzles and rotary atomizers are presented in Figure 3-23. Two-fluid nozzles have a simpler mechanical design with lower capital cost. Maintenance and operational costs are also less. This finding thus impacts the choice of atomization for industrial systems. In systems greater than 150,000 acfm with an SO_2 removal requirement of 90 percent, rotary atomizers are less expensive. Actual selection of two-fluid nozzle vs. rotary atomizers is reviewed on a project-specific basis.

Wheelabrator-Frye, in cooperation with DOE, has recently initiated a study to assess the performance of ESP's applied to spray drying systems. The pilot-scale test program is being conducted at DOE's Pittsburgh Energy Technology Center (PETC). The performance of an ESP downstream of a spray dryer will be investigated using various coals to determine the applicability of spray dryer/ESP systems and the retrofit potential for spray dryers to existing ESP installations. This test program was started in October 1983 and is scheduled to continue until the Spring of 1984.

In October 1983, Wheelabrator-Frye's pilot plant at Commonwealth Edison's Joliet Station was decommissioned after 4 years of operation. Pilot and other test operations continue at their Swenson Division test facility near Chicago and at their Air Pollution Control Division Technical Center in Pittsburgh.

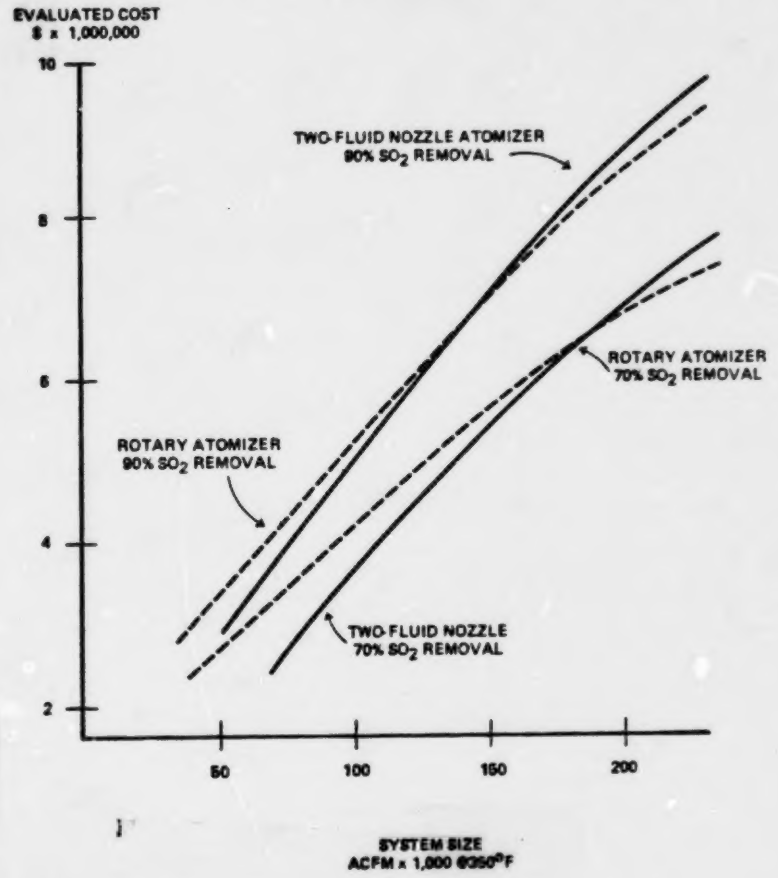

Figure 3-23. Evaluated cost comparison of two-fluid nozzles vs. rotary atomizers.

Source: Maurin, P. G., et al. See Information Sources at the end of this section.

Commercial Activities

Wheelabrator-Frye's 110,000 acfm spray dryer/fabric filter system at Austell Box Board Corporation passed compliance testing in March 1983. The SO_2 emission rate for six, EPA Method 6, test runs ranged from 0.75 to 1.05 lb/10^6 Btu, with an average of 0.85 lb/10^6 Btu for a 2 percent sulfur coal. This was within the local allowable standard of 1.20 lb/10^6 Btu. The system achieved 74 percent SO_2 removal with inlet SO_2 concentrations ranging from 1,100 to 1,200 ppm. The particulate emission rate was also within the allowable standard of 0.1 lb/10^6 Btu with an average value of 0.07 lb/10^6 Btu.

During initial operation of the Austell system, frequent plugging resulted in increased maintenance requirements for the two-fluid nozzles. This problem was caused primarily from operation at high weight percent solids in the lime feed. This situation has since been corrected by refining the nozzles and operating the system at lower approach temperatures with lower solids content in the lime feed. Despite the problem with plugging, system availability remained in excess of 95 percent during the first 5 months of operation. The two-fluid nozzles can be replaced while the system is on-line without affecting system performance. No significant nozzle wear has been experienced after approximately 10 months operation.

The joint venture Rockwell/Wheelabrator-Frye sodium-based system at Coyote Station was turned over to Montana-Dakota Utilities for operation following performance tests conducted in August 1982. Tests results for this system were reported in the last status report.

The other joint venture dry FGD system at Celanese Fibers' Amcelle Plant began operation in January 1980. System availability averaged between 90 and 95 percent for the period from October 1980 to mid-1982. It is currently not being operated because of a low steam demand and the availability of low sulfur (compliance) coal.

Wheelabrator-Frye has not sold any new systems since the Austell system was sold, but actively pursues industrial and utility boilers FGD system sales and other projects.

Information Sources

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Bradley, Wallace H., Austell Box Board Co., Telephone conversation with M. A. Palazzolo. Radian Corporation. August 11, 1983.

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Synk, Robert J. and J. B. Lawrie. "Compliance Particulate, SO_2, and NO_x Emission Testing on Coal-Fired Boiler at Austell Box Board Corporation, Austell, Georgia." Air Techniques, Inc., April 6-9, 1983.

Maurin, Peter G., et al., "Industry Drying Practices: Two-Fluid Nozzle vs. Rotary Atomization for Dry-Scrubbing Systems," Chemical Engineering Progress, April 1983, pp. 51-59.

SECTION 4

COST STUDIES OF DRY FGD TECHNOLOGIES

This section discusses three recent dry FGD cost studies. The studies are significant in that they deal with applications of dry FGD for which few cost estimates have previously been reported:

- spray dryer-based FGD applied to a high sulfur coal-fired boiler;
- spray dryer-based FGD designed for simultaneous SO_x and NO_x removal; and
- detailed cost estimates for 1,000 MWe trona and nahcolite dry injection systems.

The major results of these studies are summarized below. Available information on the technical assumptions and economic premises used in each of the studies is also presented. The reader should use caution in comparing these cost estimates to those reported elsewhere for other dry or wet FGD systems, since the assumptions used to develop various estimates may significantly affect the final result. No attempt has been made to reconcile the assumptions of the three studies discussed here.

4.1 SPRAY DRYING FOR HIGH SULFUR COAL APPLICATIONS

Conoco (Coal Research Division) recently published cost estimates for new and retrofit applications of spray drying FGD to boilers firing coal with over 3 percent sulfur (1). Reported results of the Conoco study are summarized in Table 4-1. Conoco compared the spray drying costs with estimates for wet limestone scrubbers. For grass-roots installations, the study assumptions included a 90 percent SO_2 reduction requirement to meet New Source Performance Standard (NSPS) SO_2 emission levels and a fabric filter to meet the NSPS particulate emission level. Only first-year costs (4th quarter 1982 dollars) were reported. Lime reagent requirements were reported based on test results from the Argonne high sulfur coal demonstration tests. (The Argonne tests, which were carried out on an industrial boiler firing 4.2 percent S coal are summarized in Section 3.4). Table 4-1 shows about a 4.5 percent difference in first-year costs, in terms of cost per ton of SO_2 removed, between spray drying and wet limestone scrubbing for the new (theoretical) 500 MW plant. This difference is probably within the accuracy range of the cost estimates, but does tend to indicate that spray drying may be competitive with limestone scrubbing for high sulfur coal applications. It should be noted, however, that site-specific factors such as coal properties, flue gas temperature, boiler

TABLE 4-1. COST ESTIMATES FOR LIME SPRAY DRYING AND WET LIMESTONE FGD FOR HIGH SULFUR COAL APPLICATIONS[a]

Technical and Economic Assumptions:

- Costs developed for 500 MW utility boiler located in Maryland-Delaware area.
- 3.2 wt % S coal
- New installation: NSPS requirements (90% SO_2 removal; 0.03 lb/10^6 Btu particulate matter emission limit)
- Retrofit installation: "Typical" SIP emission limits (70% SO_2 removal)
- Particulate control: New installation cases include fabric filters; Existing ESP used for retrofit cases.
- Lime reagent requirements for spray drying based on results from Argonne high sulfur coal demonstration tests (see Section 3.4 of this report).
- 16.5% capital charge
- First-year costs based on 4th quarter 1982 dollars.

Process	New Installation (90% SO_2 removal) \$/ton SO_2 removed	Retrofit Installation (70% SO_2 removal) \$/ton SO_2 removed
Spray Drying FGD	360	319
Wet Limestone FGD	377	373

[a] Reference 1.

size and operating rate, and reagent transportation costs can significantly impact the relative costs of the two systems for a particular plant.

For the retrofit case, the Conoco study assumed a 70 percent SO_2 removal requirement, based on typical State Implementation Plan (SIP) emission limits. The spray dryer or the limestone scrubber was assumed to be installed between the boiler and an existing ESP. No retrofit factor assumption was reported. The resulting estimates, as shown in Table 4-1, indicate that retrofitted lime spray drying is 14.5 percent less costly than the retrofitted wet limestone system, based on first year costs per ton of SO_2 removed. Although this difference is likely to be within the accuracy of the cost estimates, it does indicate a larger advantage for the spray dryer at lower SO_2 removal requirements. One key assumption for the retrofit case was that the existing ESP did not have to be modified to handle the increased particulate loading associated with the spray dryer. This assumption was based on resistivity measurements of spray dryer particulates made at the Argonne system. These measurements indicated that the spray dryer particulates were similar to that of fly ash from many eastern medium or high sulfur coals (see Section 3.4). However, site-specific factors such as the specific collection area (SCA) and precipitation rate parameters of the existing ESP could require ESP modifications that may change the relative economics of the lime spray drying and wet limestone FGD. Additionally, other site-specific factors such as land and space availability for retrofit could affect the relative economics.

4.2 SPRAY DRYING FOR SIMULTANEOUS SO_x AND NO_x REMOVAL

Niro Atomizer recently compared the costs of simultaneous SO_x/NO_x removal, using their conventional spray drying FGD system and a sodium hydroxide additive, to the costs of a conventional limestone wet scrubber combined with an ESP and a selective catalytic reduction (SCR) system for NO_x removal (2). (The spray dryer-based simultaneous SO_x/NO_x process is discussed in Section 3.11).

Table 4-2 presents the results of this study, which was based primarily on results from testing the simultaneous SO_x/NO_x process at Joy/Niro's Argonne system. The study assumptions included:

- 65 percent NO_x removal,
- 90 percent SO_2 removal, and
- 3 percent sulfur coal fired in a 500 MW utility boiler.

The lime reagent requirement assumed was not reported. The costs for the limestone scrubbing and SCR systems were based on earlier cost studies of FGD and NO_x control techniques (3,4,5). The reader is referred to those studies for details on the costing assumptions used by Niro, since the assumptions were not reported in Reference 2.

TABLE 4-2. COST COMPARISON OF SPRAY DRYER-BASED SIMULTANEOUS SO_2/NO_x REMOVAL WITH LIMESTONE WET SCRUBBING/ SELECTIVE CATALYTIC REDUCTION

Technical and Economic Assumptions:

- 500 MW new utility boiler (location assumption not reported) burning 3% S coal
- 65 percent NO_x removal
- 90 percent SO_2 removal
- 2-year life for SCR catalyst
- Capital requirement levelization factor: 0.18
- O&M cost levelization factor: 1.9
- 30-year plant life

Cost Item	Spray Dryer System	Wet Limestone Plus SCR
Capital Requirement (10^6\$)	85	135 = 105 (FGD) + 30 (SCR)
First-year Operating & Maintenance (10^6\$)	19.5	21.8 = 17.2 (FGD) + 4.6 (SCR)
Levelized Capital (mills/kWh)	4.8	7.4
Levelized O&M (mills/kWh)	11.3	12.7
Total Levelized Cost (mills/kWh)	16.1	20.1

[a] Reference 2

[b] Year of dollars of estimate not reported

Niro's estimates indicate that the capital costs of lime spray dryer simultaneous SO_x/NO_x removal are about 37 percent less than for the limestone wet scrubbing/SCR system. The first-year operating and maintenance costs show about a 10.5 percent difference. Levelized costs, based on a 30-year plant life, are about 20 percent lower for the spray dryer-based system.

4.3 DRY INJECTION OF SODIUM COMPOUNDS

Stearns-Roger, Inc. and EPRI recently reported cost estimates for dry injection FGD based on the demonstration-scale test work at Public Service of Colorado's Cameo Station (6,7). The estimates were developed for trona and nahcolite dry injection, as applied to two new 500 MW utility boilers burning low sulfur western coal. These estimates were compared with costs for lime spray drying FGD. The results of the study are summarized in Table 4-3. Major assumptions used in the study included:

- Midwest plant location (Wisconsin)
- 70 percent SO_2 removal requirement for spray drying and trona dry injection;
- 75 percent SO_2 removal requirement for nahcolite dry injection;
- 0.48 percent S coal with a heating value of 8020 Btu/lb; and
- delivered reagent costs of \$100/ton for nahcolite, \$75/ton for trona, and \$60/ton for lime

Other assumptions used in developing the costs are discussed.

4.3.1 Capital Costs

The capital cost components for the three systems examined are shown in Table 4-5. Dry injection system capital costs are about equally distributed between the reagent receiving and handling area and the pulverized area. The design basis used in the study includes pressurized ball mill pulverizers with internal classification, the same type of mill typically used for coal pulverization. Reagent receiving and handling systems are enclosed to prevent sorbents from absorbing moisture and to prevent potential sodium run-off problems that would occur with exposed storage. Pulverized sorbent is injected into the flue gas duct work upstream of the fabric filter.

4.3.2 First-Year O&M and Levelized Costs

First year operating and maintenance costs and levelized costs of the three systems are presented in Tables 4-6 and 4-7, respectively. The O&M estimates show that reagent costs are the most significant operating cost

TABLE 4-3. SUMMARY OF COMPARISON OF DRY INJECTION AND SPRAY DRYING COSTS FOR LOW SULFUR COAL-FIRED BOILERS ($1983)[a,b]

Cost Item	Nahcolite Dry Injection	Trona Dry Injection	Lime Spray Drying
Capital Requirements ($/kW)	90.4	89.1	175.9
First-year Operating and Maintenance ($/kW)	17.6	15.1	14.6
Levelized Costs (mills/kWh)			
- Capital	2.4	2.4	4.7
- O&M	7.2	6.2	6.0
Total[c]	9.6	8.6	10.8

[a] Reference 6.

[b] See Table 4-4 for technical and economic assumptions used in developing cost estimates.

[c] May not add to total because of round-off error.

TABLE 4-4. TECHNICAL AND ECONOMIC ASSUMPTIONS USED IN ESTIMATING DRY INJECTION COSTS[a]

Base Case:

- Two new 500 MWe utility boilers in Kenosha, Wisconsin
- 70% SO_2 removal for trona dry injection and lime spray drying; 75% SO_2 removal for nahcolite dry injection
- 0.48% S Western coal; 8020 Btu/lb; 6.4% ash
- Reagent ratios:
  - lime spray drying - 0.9 moles CA^{++}/mole SO_2 inlet
  - nahcolite dry injection - 0.85 moles Na_2^{++}/mole SO_2 inlet
  - trona dry injection - 1.2 moles Na_2^{++}/mole SO_2 inlet
- Reagent purity, %:
  - lime - 90
  - nahcolite - 70.3 as active sodium
  - trona - 85.9 as active sodium
- Reagent costs: (FOB at plant)
  - lime - \$60/ton
  - nahcolite - \$100/ton
  - trona - \$75/ton
- Waste disposal costs:
  - spray drying \$4.60/ton
  - dry injection: \$7.40/ton
- Other economic assumptions - See References 8, 9

Capital Costs

- Major equipment items for dry injection: Reagent Receiving and Storage Area -- railroad spur and unloading facility, bulk storage silos, pneumatic conveying systems; Pulverization Area -- day storage silo, pulverizer, classifier and blower, pneumatic injection; fabric filter and I.D. fan differential costs from higher grain loading, increased pressure drop.

Operating and Maintenance Cost -- 65% capacity factor; reagent and waste disposal costs as indicated above.

Levelized Costs

- 15.3% annual capital charge; 2.31 levelization factor for annual O&M costs.

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[a] Reference 6.

TABLE 4-5. BASE CASE DRY INJECTION AND SPRAY DRYING CAPITAL COSTS[a]

Emission Control Area	Equipment Area	Nahcolite Injection ($/kW)	Trona Injection ($/kW)	Spray Drying ($/kW)
Flue Gas Desulfurization	Pulverization (and slaking)	5.0	4.5	2.4
	Reagent receiving and storage	4.4	4.4	2.9
	Absorber	NA[b]	NA	52.2
	Ductwork	NA	NA	8.5
	Other[c]	12.8	11.8	49.5
	Total FGD	22.1	20.8	115.5
Particulate Control	Fabric filter and solids handling	49.3	49.3	43.5
	Other[c]	19.1	19.1	16.9
	Total Particulate	68.3	68.3	60.4

Basis: 2-500 MWe units; 0.48%, sulfur coal; 70% SO_2 removal for trona and lime spray dryer; 75% SO_2 removal for nahcolite; $1983.

[a] Reference 6

[b] NA = Not Applicable

[c] Other costs include engineering and design, contingencies, and construction.

TABLE 4-6. BASE CASE ANNUAL OPERATION AND MAINTENANCE FOR DRY INJECTION AND SPRAY DRYING[a]

Emission Control Area	O&M Item	Nahcolite Injection ($/kW)	Trona Injection ($/kW)	Spray Drying ($/kW)
Flue gas desulfurization	Reagent[c]	10.9	8.4	1.8
	Maintenance and labor	0.9	0.9	6.4
	Power	0.6	0.6	2.2
	Water	NA[b]	NA	0.2
	Waste disposal[d]	1.3	1.4	0.3
	Total	13.7	11.3	10.9
Particulate Control	Maintenance and labor	0.8	0.8	0.8
	Power	1.5	1.5	1.5
	Materials and other variable costs	1.5	1.5	1.5
	Total	3.8	3.8	3.8

Basis: 2-500 MWe units; 0.48% sulfur coal; 70% SO_2 removal for trona and lime spray drying; 75% SO_2 removal for nahcolite; $1983.

[a] Reference 6.

[b] NA = Not Applicable.

[c] Nahcolite at $100/ton, trona at $75/ton, lime at $60/ton.

[d] Nahcolite and trona waste disposal at $7.40/ton and lime spray dryer waste disposal at $4.60/ton.

TABLE 4-7. LEVELIZED BUSBAR COSTS FOR DRY INJECTION AND SPRAY DRYING[a]

Emission Control Area	Cost Item	Nahcolite Injection (Mills/kWh)	Trona Injection (Mills/kWh)	Spray Drying (Mills/kWh)
Flue gas desulfurization	Reagent	4.4	3.4	0.7
	Operation and maintenance (excluding reagent)	1.2	1.2	3.7
	Capital	0.6	0.6	3.1
	Total FGD	6.2	5.1	7.6
Particulate Control	Operation and maintenance	1.6	1.6	1.6
	Capital	1.8	1.8	1.6
	Total Particulate	3.4	3.4	3.2
	Total System	9.6	8.6	10.8

Basis: 2-500 MWe units; 0.48% sulfur coal; 70% SO_2 removal for trona and lime spray drying; 75% SO_2 removal for nahcolite; $1983.

[a] Reference 6.

for the dry injection systems. On a weight basis, the dry injection systems require over three times the amount of reagent as compared to the lime spray dryer. Operational labor and maintenance costs were estimated to be significantly lower for the dry injection systems. Waste disposal costs are higher than for spray drying, however, due to the soluble sodium compounds in the dry injection system waste. A divided-cell clay-lined landfill was assumed in calculating waste disposal costs for the dry injection systems.

Reagent costs are also the major component of the dry injection system levelized costs. Table 4-7 shows the nahcolite system to have about 11 percent lower levelized costs than lime spray drying, while trona dry injection costs are 20.4 percent lower.

4.3.3 Sensitivity Analysis

The study also examined the sensitivity of the estimated costs to various capital- and operating-related factors. The study concluded that the relative costs of the dry injection and spray drying systems depended primarily on:

- delivered reagent cost;
- coal sulfur content, and
- SO_2 removal requirements.

Reagent Costs - Reagent costs will depend primarily on plant location and the availability of trona or nahcolite. The study concluded that, because of the large volume of reagent required and the need to protect the reagent from moisture, the power plant should be located near an existing rail spur.

The study also concluded that the development of dry injection will depend greatly on the availability of trona or nahcolite. Trona is currently mined in the western U. S. The annual demands for the two 500 MW units examined in this study would be about 6 percent of the capacity of the largest domestic mining company.

Nahcolite, which is associated with the oil stale deposits in the western U.S. is not currently mined in commercial quantities and thus its cost and availability are uncertain.

Coal Sulfur Content The study found nahcolite dry injection (at $100/ton delivered) to be the economic choice (relative to spray drying FGD) for coals with sulfur contents up to about 0.6 percent, based on total levelized costs. Trona was less costly up to a coal sulfur content of about 0.8 percent. These trends are due to the higher reagent requirements and higher reagent costs associated with dry injection systems.

SO$_2$ Removal Requirement The study found that, in terms of total levelized costs, dry injection is more economical than spray drying FGD for SO$_2$ removal requirements of between 80 and 85 percent for a 0.5 percent S coal. (These relative economics are based on the delivered reagent costs listed in Table 4-4.)

Other Factors Influencing Costs Other factors found to influence the relative economics of the spray drying and dry injection systems were generating unit size and reagent purity.

4.4 REFERENCES

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6. Naulty, D. J., et al. (Stearns-Roger Engineering Corporation) and Richard Hooper (EPRI)), "Economics of Dry FGD by Sorbent Injection", Presented at 76th Annual Meeting of Air Pollution Control Association, Atlanta, GA, June 19-24, 1983.

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8. Stearns-Roger Engineering Corp. Economic Evaluation of Flue Gas Desulfurization Systems. EPRI CS-3342. Electric Power Research Institute, Palo Alto, California, December 1983.

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SECTION 5

DRY FGD WASTE DISPOSAL

The collective experience of the U. S. utilities and industries in operating wet scrubbers and disposing of scrubber waste (sludge, fly ash) has been studied and documented fairly extensively. Studies have been aimed at (1) developing a data base on sludge and ash handling procedures, (2) providing independent evaluations of the sludge fixation processes, (3) quantifying variables affecting the solubility of trace elements and potentially toxic species from solid waste by-products, and (4) establishing guidelines for the construction of sludge disposal facilities.

Similar efforts directed at characterization, disposal, and utilization of waste from dry SO_2 control systems are now well underway. Studies conducted in the last 3 years have generated a substantial data base on the chemical and physical characteristics of dry FGD wastes. As more commercial dry FGD systems begin to operate, an even broader data base should emerge. This section presents some of the findings of recent research work in the area of dry FGD waste characterization.

5.1 PHYSICAL AND CHEMICAL CHARACTERISTICS

Under the Resource Conservation and Recovery Act (RCRA), solid waste is defined as "any garbage, refuse, sludge from a waste water treatment plant, water supply treatment plant, or air pollution control facility . . . ." The RCRA further defines a hazardous waste as any solid waste not excluded under Section 261.4 of RCRA. Among these excluded wastes are fly ash, bottom ash, slag, and FGD waste from coal burning sources. If not specifically excluded, then hazardous wastes are either listed in Subpart D, contain chemicals listed in Subpart D, or exhibit hazardous characteristics. Dry FGD waste is not listed in Subpart D and does not contain chemicals listed in Subpart D or exhibit any hazardous characteristics. (The hazardous characteristics mentioned under the law are ignitability, corrosibility, reactivity, and toxicity). Results from several early studies to characterize dry FGD wastes were presented in previous status reports. Summarized below are the results of more recent studies.

Argonne National Laboratory (ANL) has evaluated the wastes from their lime-based, spray dryer/fabric filter system through elemental analysis, leachate analysis and plant growth experiments (1). The Argonne spray drying system removes 80 percent of the SO_2 from the flue gas of a boiler that burns 3.0 to 3.5 percent sulfur coal.

An elemental analysis was conducted on both unblended flyash samples and spent sorbent samples containing very little flyash. Table 5-1 compares these results to those from three flyash/spent sorbent mixtures. These

TABLE 5-1. ELEMENTAL ANALYSIS OF WASTE SAMPLES FROM ARGONNE AND THREE UTILITY SYSTEMS

	Concentration, ppm				
Element	ANL Flyash	Research-Cottrell Waste	Rockwell-Joliet Station Waste	Joy/Niro Riverside Waste	ANL Spent Sorbent
Aluminum	68,100	41,000	71,000	58,000	3200
Antimony	<500	<8	<8	<8	<500
Arsenic	<500	14.2	33	30	<500
Barium	130	400	190	350	20
Beryllium	40	5.1	8.5	4.3	4
Boron	500	ND[a]	ND	ND	500
Cadmium	70	<1.0	<1	<1.0	<5
Calcium	7100	170,000	97,000	150,000	283,000
Chromium	130	50	54	52	20
Cobalt	80	14	15	4.9	<10
Copper	150	84	81	16	40
Iron	367,000	22,000	44,000	20,000	6300
Lead	150	4.4	17	<20	130
Magnesium	3000	12,000	13,000	15,000	5500
Manganese	210	200	110	630	100
Mercury	ND	ND	ND	ND	ND
Molybdenium	<10	<0.5	8.7	16	ND
Nickel	460	26	39	215	30
Potassium	2600	3100	6300	4300	1700
Selenium	ND	6.1	4.7	<20	ND
Silver	<10	<0.5	0.5	<0.5	ND
Sodium	2800	12,000	15,000	2700	1400
Strontium	250	1800	1800	1900	170
Thallium	ND	<25	<30	<25	ND
Tin	<30	<30	<30	<36	<30
Titanium	4000	4900	5200	3100	230
Vanadium	270	70	120	580	30
Zinc	330	43	92	37	120

[a] Not Detected.

Source: Reference 1.

Source: Reference 1.

mixtures were obtained from Research-Cottrell's pilot plant at the Comanche Station, Rockwell International's pilot plant at the Joliet Station, and Joy/Niro's demonstration unit at the Riverside Station. All three treated flue gas from low sulfur Western coal. The major differences in elemental composition between Argonne's waste and the other wastes were attributed to the fact that low sulfur Western coals were combusted at the utility stations, while high sulfur midwestern coal was combusted at Argonne.

Leachate analyses were also conducted on sorbent/flyash mixtures according to EPA's Extraction Procedure (EP) Toxicity Test. The results presented in Table 5-2 showed that the dry scrubber wastes would be classified as nonhazardous under the Resource Conservation and Recovery Act (RCRA). A nonhazardous classification means that the elemental concentration within the leachate did not exceed 100 times the concentration specified in the Drinking Water Standard. All elements tested were within this limit, but it should be noted that chromium levels were only within 2 percent of exceeding the allowable concentration.

TABLE 5-2. A COMPARISON OF THE ARGONNE EP TOXICITY TEST RESULTS WITH DRINKING WATER STANDARDS

	Concentration, ppm	
Element	Interim Primary Standards	EP Toxicity Results
Arsenic	0.05	0.220
Cadmium	0.01	0.047
Chromium	0.05	4.9
Lead	0.05	0.058
Mercury	0.002	0.0024
Selenium	0.01	0.028
Silver	0.05	0.053

Source: Reference 1

The effect of pH on the composition of the leachate was also investigated for the Argonne dry FGD waste. The leachate concentration of boron and chromium increased as the pH (or sorbent content) of the dry scrubber wastes increased. Thus when alkaline scrubber wastes are first placed in a landfill, considerable boron and chromium leaching may occur. This leaching should decrease with time as the pH of the waste decreases.

In contrast, Argonne found that the concentration of cadmium and lead in the leachate decreased with increasing pH. The highest concentrations of antimony, arsenic, mercury, and selenium were observed at a pH of approximately 5.

In another experiment, corn and soybeans were grown on soil that was treated with dry scrubber wastes. As the amount of waste increased from 0 percent to 4 percent by weight, the biomass of these plants decreased. In addition, the leaves of corn and soybeans grown on soil containing dry scrubber wastes had as much as 20 times more boron compared with those grown without scrubber wastes.

Niro Atomizer has evaluated the physical and chemical characteristics of waste solids generated from their SO_x/NO_x dry scrubbing process (2). These tests were conducted at Argonne National Laboratories.

As shown in Table 5-3, the chemical composition of the waste produced from the combined SO_x/NO_x process is very different from that produced via a conventional dry scrubber. The former has much more sulfate than sulfite and contains 3 percent nitrate from the removal of NO_x.

Compared with conventional dry scrubber waste, the SO_x/NO_x waste has a higher dry density, but similar compressive strengths and permeabilities. These data are presented in Figure 5-1 and Table 5-4.

The leachate quality of the SO_x/NO_x waste product is such that it would be classified as nonhazardous under RCRA. The data in Table 5-5 show that, except for the concentration of nitrate, the leachate from SO_x/NO_x waste is similar to that from the spray dryer removing SO_2 only. Since nitrate concentrations are elevated in the SO_x/NO_x waste, it may need to be disposed of in a lined site.

Under Niro's funding, the Marien Sciences Research Center in Stony Brook, New York is conducting laboratory and in-situ tests to assess the feasibility of ocean disposal for dry FGD wastes (3). The waste samples were obtained from Joy/Niro's spray dryer/fabric filter system at Northern States Power Company's Riverside Station. The laboratory tests include an analysis of the dry waste's permeability and compressive strength and an elemental analysis of the leachate. For the in-situ experiments, eight cylinders (6 inches high and 4 inches in diameter) have been placed in the sea to determine if they will maintain their integrity in the marine environment. Results are not available at this time.

Under contract to EPRI, Radian Corporation is conducting tests on four waste samples from Joy/Niro's spray dryer/fabric filter system at Northern States Power Company's Riverside Station. Tests are being conducted to determine the compressive strength, permeability, chemical composition of the solids fraction, and chemical composition of the leachate. Results are not available at this time. Similar analyses are also being conducted on wastes from EPRI's Arapahoe pilot plant.

TABLE 5-3. CHEMICAL COMPOSITION (wt%) OF THE WASTE PRODUCED FROM SO_2 AND COMBINED SO_2/NO_x SYSTEMS

Component	Chemical Composition (wt%) SO_2 Removal	Chemical Composition (wt%) SO_2/NO_x Removal
Sulfite as $CaSO_3 \cdot \frac{1}{2}H_2O$	59	16
Sulfate as $CaSO_4 \cdot 2H_2O$	16	43
Nitrate as $Ca(NO_3)_2$	∿ 0	3
Excess Alkalinity as $Ca(OH)_2$	15	21
Ash & Inerts	9	8
Moisture	1	1
Na_2SO_3	∿ 0	9

Source: Reference 2.

TABLE 5-4. COMPRESSIVE STRENGTH AND PERMEABILITY OF THE WASTE PRODUCED FROM SO_2 AND COMBINED SO_2/NO_x REMOVAL SYSTEMS[a]

Compressive Strength (kPa)	SO_2 Product	SO_2/NO_x Product
1 Day	120	110
7 Days	180	200
30 Days	480	340
56 Days	600	580
Permeability (10^{-6} cm/s)		
1-2 Days	2.5	6

[a] All samples are compacted to a dry density of 960-980 kg/m^3 (59.8 - 61.1 lb/ft^3).

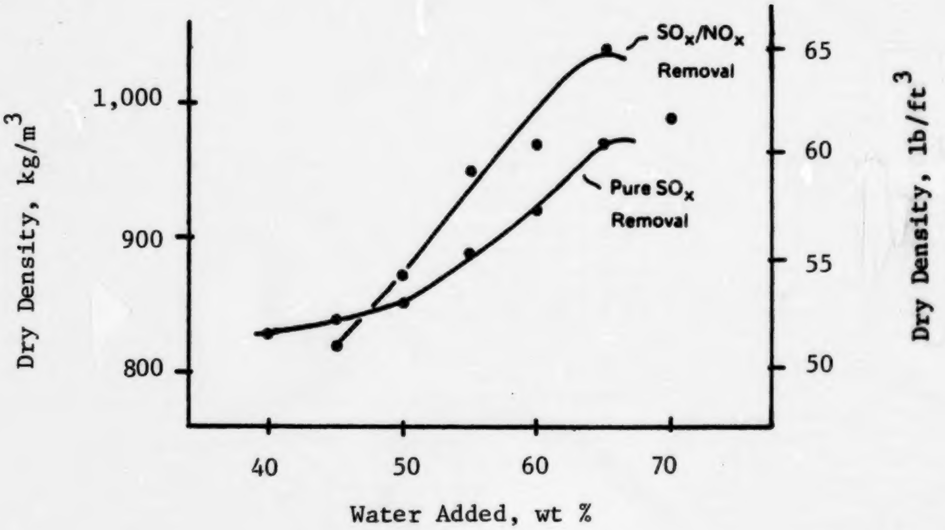
Source: Reference 2.

TABLE 5-5. LEACHATE QUALITY OF THE WASTE PRODUCED FROM SO_2 AND COMBINED SO_2/NO_x REMOVAL SYSTEMS[a]

	EPA-Drinking Water Standards mg/l	SO_2 Removal mg/l	SO_2/NO_x Removal mg/l
Arsenic	0.05	0.001	0.001
Barium	1.0	< 0.5	< 0.5
Cadmium	0.010	< 0.005	< 0.005
Chromium	0.05	0.010	0.012
Lead	0.05	< 0.05	< 0.05
Mercury	0.002	< 0.002	< 0.002
Nitrate (as N)	10	2	260
Selenium	0.01	0.004	0.004
Silver	0.05	< 0.01	< 0.01

[a] Test carried out according to EPA toxic extraction procedure.

Source: Reference 2.



Source: Reference 2.

Figure 5-1. Density variation with moisture in the waste product from SO$_x$ and combined SO$_x$/NO$_x$ removal systems.

5.2 REFERENCES

1. Farber, Paul S., C. David Livengood and John L. Anderson (Argonne National Laboratory). Leachate of Dry Scrubber Wastes, Paper # 83-29.2, presented at the 76th Annual Meeting of the Air Pollution Control Association, Atlanta, Georgia, June 19-24, 1983.

2. Felsvang, Karsten, Per Morsing, and Preston Veltman (Niro Atomizer). Acid Rain Prevention Thru New SO_x/NO_x Dry Scrubbing Process. Presented at the 8th FGD Symposium, New Orleans, Louisiana, November 1-4, 1983.

3. Parker, Jeff (Marine Sciences Research Center, State University of New York at Stony Brook). Telephone conversation with M. A. Baviello, Radian Corporation, November 14, 1983.

APPENDIX A

CONVERSION FACTORS

To Convert From English	To SI	Multiply By
cfm	m^3/hr	1.70
ft	m	0.305
gr/scf	kg/m^3	0.00229
in.	m	0.0254
in. H_2O	Pa	249
lb	kg	0.454
gal	m^3	3.79
gal/1,000 ft^3	liters/m^3	0.13
BTU	joule	0.252
short ton	tonne	0.91

The temperature conversion formula between English and SI units is:

$$\frac{°F - 32}{9} = \frac{°C}{5} \qquad \text{(A-1)}$$

where: °F = degrees Fahrenheit
°C = degrees Celsius